Army Research Laboratory

Effects on SADARM Trajectory Simulations With Local RAOBs and BFM Data for the RDAP/LUT Firings

by Terry C. Jameson
Saba A. Luces
David I. Knapp

ARL-TR-2720 December 2002

NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

Citation of manufacturers' or trade names does not constitute an official endorsement or approval of the use thereof.

Army Research Laboratory
White Sands Missile Range, NM 88002-5513

ARL-TR-2720 December 2002

Effects on SADARM Trajectory Simulations With Local RAOBs and BFM Data for the RDAP/LUT Firings

Terry C. Jameson, Saba A. Luces, and David I. Knapp
Computational and Information Sciences Directorate

Preface

A meteorological (Met) analysis was performed on data collected during Sense and Destroy Armor (SADARM) artillery live firings that occurred at Yuma Proving Ground, Arizona. Actual SADARM impact data were compared against predicted impacts derived from a trajectory simulation program. Two types of Met data were entered in the trajectory simulator: those from standard battlefield weather balloons and those that were computer model generated in order to test which type most accurately represented the "real" atmosphere. For the most part, the model-generated Met data were the most accurate relative to the live firings in time and space. It is hoped that this study will establish the validity of using the modeled Met data in the future for live artillery aiming purposes.

Contents

Figures

Tables

Figures

Tables

Executive Summary

The research described herein was funded by the Office of the Project Manager, Artillery Munitions Systems. The U.S. Army Research Laboratory was tasked to perform meteorological (Met) analyses of data collected during the Sense and Destroy Armor (SADARM) Reliability Determination/Assurance Program (RDAP) and Limited User Test (LUT) artillery firings in January and April/May, 2000, at Yuma Proving Ground, Arizona. Actual SADARM impact data were compared against predicted impacts derived from the general trajectory model Version 3 (GTRAJ3) artillery trajectory simulation program (a simulator developed by the U.S. Army Armament Research, Development, and Engineering Center that relies heavily on Met data input). Two types of Met data were entered in the GTRAJ3 in order to test which type most accurately represented the "real" atmosphere. They were measured radio wind sounding (rawinsonde) balloon observations (RAOBs), which are the type of Met data currently used for aiming calculations by Army artillery units, and data generated by a Met forecast model, called the Battlescale Forecast Model (BFM).

Previous SADARM Met research, conducted on a data set from Ft. Greely, Alaska, produced mixed results. Because of the complex terrain and variable local wind conditions encountered in the test area, the Ft. Greely Met study was somewhat inconclusive. This ensuing study was conducted with the intent of obtaining more definitive results.

The SADARM RDAP and LUT firings were over a range of slightly less than 20 km and were aimed with RAOB data that were very current (less than 2 hours old). Even during such optimum conditions for the use of weather balloon data in artillery aiming, the BFM forecasts out-performed the RAOBs in accurately representing the "real" atmosphere relative to the SADARM trajectories in time and space. It is hoped that this study, along with future research results, will establish the validity of using the BFM (or a similar model) to obtain Met data for aiming live artillery.

INTENTIONALLY LEFT BLANK

EFFECTS ON SADARM TRAJECTORY SIMULATIONS WITH LOCAL RAOBS AND BFM DATA FOR THE RDAP/LUT FIRINGS

1. Introduction

1.1 Purpose and Overview

The purpose of this study was to evaluate the suitability of mesoscale[1] meteorological (Met) computer model output for artillery aiming applications. The study was requested and funded by the Office of the Project Manager, Artillery Munitions Systems (OPM-ARMS). It covers live firing missions of the Sense and Destroy Armor (SADARM). Current battlefield doctrine involves the use of radio wind sounding (rawinsonde) weather balloon observations (RAOBs) released near the guns to obtain the necessary Met information for generating artillery computer Met messages (CMMs). CMMs generated in this manner have limitations in their effectiveness, particularly for longer range artillery and for warheads that interact with the low altitude weather in the target area. They are assumed to adequately represent the atmosphere along the entire artillery round's trajectory, an assumption that does not always hold true. The balloon-borne RAOB has spatial and temporal constraints that can adversely affect artillery and other military applications. The spatial limitations occur since the balloon can easily drift many kilometers from its launch point (and perhaps far from the battlefield area of interest) and because the weather at the launch point may differ greatly from the weather at the target. Temporal limitations exist since a RAOB often takes 1 or more hours to reach the peak of its ascent, with additional time required to process and disseminate the information. Also, it is not always possible to launch a RAOB near the time of firing. For these reasons, a RAOB-based CMM (RCMM) can introduce errors into the artillery aiming solution.

The U.S. Army Research Laboratory's (ARL) Battlescale[2] Forecast Model (BFM) was used to generate *forecast* CMMs (herein called "FCMMs") for comparison against those data obtained from RAOBs. The BFM predicts Met conditions at desired points in space and time (in this case, at several points along the trajectory and at the firing time). Thus, an FCMM, generated by a model such as the BFM, has the potential of more accurately representing the atmosphere to allow more precise artillery aiming.

[1]The term "mesoscale" here refers to meteorological phenomena of typical size 2 to 20 km, which are to be predicted by the forecast model.
[2]The term "battlescale" refers to an area on the order of 200 to 500 km^2, which would encompass the dimensions of a typical battlefield.

1.2 Background

An earlier study (funded in part by the OPM-ARMS) was of the SADARM Initial Operational Test and Evaluation (IOT&E) conducted at Ft. Greely, Alaska, during the summer of 1998[3]. A combination of factors rendered the IOT&E study somewhat inconclusive [1]. However, it was apparent that atmospheric variability along the trajectory, the effects of rugged terrain on the winds, and unknown Met conditions in the target area could all have had an adverse effect in the aiming accuracy of the guns during that test. OPM-ARMS requested ARL to conduct an ensuing study of the reliability determination/assurance program-2A (RDAP) and the Limited User Test (LUT) at the Yuma Proving Ground (YPG), Arizona, Kofa firing range, to more conclusively determine whether FCMMs obtained from a Met model such as the BFM could be beneficial to SADARM.

Besides Met conditions, there are a host of other factors that affect artillery aiming accuracy. These include muzzle velocity, propellant temperature, target area and gun area elevation above sea level, gun azimuth and elevation angles, and the geographic latitude where the firings take place, to name the primary ones. These factors were precisely known for the analyses described herein and thus were eliminated as variables that could affect the outcome. Therefore, only the CMMs remained as variables.

Along with these post-analyses, ARL conducted real-time BFM runs during the LUT in support of the live firings. The purpose of these real-time runs was to provide short-term forecast displays of wind and temperature fields for SADARM test personnel (and not to produce CMMs).

2. The SADARM Weapon System

SADARM is a submunition delivered by a 155-mm artillery round. In its RDAP/LUT configuration, it was fired over a range of about 20 km with a peak of its trajectory (apogee) of just under 5 km above ground level (AGL). Somewhere between 1500 and 1000 meters AGL on the downward leg, the artillery round ejects two submunition canisters. Each canister deploys a ram-air inflated decelerator (RAID) parachute. At around 500 meters AGL, a second chute is deployed (called the vortex ring parachute or VRP). The VRP causes the descending canister to spin, allowing the submunition to perform a search. Millimeter-wave and infrared sensors scan for armored vehicle targets during the VRP descent phase, beginning at 130 meters' AGL. The maximum radius of the search pattern is 75 meters. When a target is sensed, an explosively formed penetrator (EFP) fires from the canister.

[3]A project report dated 6 November 2000 covering this research was delivered to the OPM-ARMS.

The characteristics of the EFP performance are not pertinent to this study; consequently, no EFP operational results are discussed. All references to "impacts" in this study concern RAID ground impacts. From a ballistics standpoint, RAID reacts to the atmospheric conditions within the final 1000 meters' AGL in an almost identical fashion to the submunition canister descending on the VRP. Consequently, the RAID impact points (which are precisely surveyed) may be assumed to represent the impact of the SADARM submunition canisters. Once again, each round produces *two* RAID impacts, one from the "forward" and the other from the "aft" submunition canister.

There were 42 targets (armored self-propelled howitzers) for the RDAP, situated in a rectangular array. Each target housed a gasoline generator that powered heaters and blowers that served as a heat source for the SADARM infrared sensors. The LUT target array consisted of 12 targets arranged in a threat defensive array across the same general target area as for the RDAP. These targets were different kinds of vehicles and a tent.

3. The Battlescale Forecast Model

The BFM is comprised of three modules: pre-processing, the actual predictive model, and post-processing. The pre-processing or "initialization" module consists of input file-handling routines and a three-dimensional (3-D) objective analysis (3DOBJ) routine that captures all recent local and large scale Met data available at the forecast time and produces the initial fields required to start the forecast module. The 3DOBJ routine also provides time-dependent lateral boundary values during the model run. Initialization data used for the SADARM RDAP/LUT cases consisted of large scale forecast fields from the Navy Operational Global Atmospheric Prediction System (NOGAPS) 1-degree horizontal grids. (Such fields are required for any mesoscale model to help account for larger scale atmospheric changes at the desired forecast hour.) Additional initialization data came from standard regional RAOBs launched twice each day at several locations across the southwestern United States. Most importantly, the last source of initialization data was a "local" RAOB launched near the trajectory of the rounds approximately 60 to 120 minutes before each SADARM firing. The BFM (as for any mesoscale model) is known to produce more accurate forecasts when initialized with a local RAOB. (This was clearly demonstrated in the IOT&E study [1]). All initial data are interpolated to 55 flat levels by the 3DOBJ, and a Barnes-type analysis is performed (a distance-weighted interpolation from the balloon location to produce data at each horizontal grid point). Finally, the flat levels are linearly interpolated in the vertical to the 32 terrain-following levels required by the forecast module. The interpolation to terrain-following levels requires a terrain database. In most cases, a world-wide military digital terrain elevation database is used by the BFM, as was the case for the RDAP/LUT analyses.

The forecast module used as part of the BFM package is Yamada's higher order turbulence model for atmospheric circulations (HOTMAC). This module accepts the 3DOBJ output and conducts the actual predictive process. To produce the true 0-hour wind fields in a dynamically adjusted fashion, a 3-hour model spin-up integration is performed. During the spin-up, model surface temperatures can also be nudged to record surface observations from the model domain area, which were valid at the initial model time. HOTMAC also includes physical parameterizations for turbulent mixing, both long- and short-wave radiative transfer, the surface energy budget, and cloud and precipitation formation **[2,3]**. During the HOTMAC run, forecast output is produced by the atmospheric predictive equations solved in a hydrostatic formulation along with nudging of parameters toward the larger scale NOGAPS solutions.

The third BFM module consists of post-processing of HOTMAC output in order to produce forecasts of five standard variables: temperature, wind speed, wind direction, moisture, and height or pressure at each level of model output. For SADARM applications, gun area[4], apogee, and low level target area Met parameter forecasts were produced from this final module. The BFM was run to produce output at a 5-km horizontal grid resolution across a 300-km by 300-km domain centered near the apogee.

In the original BFM software, CMMs were created by linear interpolation from 3-D grid points surrounding the apogee point itself. However, because of two considerations (the desire to use the surface[5] wind at the gun and the possibility of the terrain height at the apogee point being higher than that at the gun location), the BFM post-processing module was modified. To address the first factor, a "merged" CMM was produced that uses surface winds (Line 0 in the Met message*) at the gun location*. The remaining levels (Line 1 upward to the apogee height to Line 12 in the case of SADARM) are *at the apogee point*. The advantage of such a "merged" profile was that Met data that were valid at the firing point for the lowest level were used instead of at the apogee (approximately 10 km away). In a situation where the second factor applies, CMM Lines 1, 2, and so forth are also from the gun location. The CMM lines switch to the apogee point only when the terrain at that location is cleared.

A disadvantage of using BFM Met data that are valid at the gun location (for lowest level(s)) is that the atmospheric conditions in the target area are not represented in the GTRAJ3 simulation. However, the BFM produces a second Met message, called a MET-TALL (meaning meteorology-target area low level)[6]. The MET-TALL, as its name implies, is a Met message that has been interpolated to the *target area*. Both the CMM and the MET-TALL were used in each GTRAJ3 simulation in this study in order to more accurately incorporate Met information at the gun, apogee, and target.

---

[4]The BFM uses "sectors" to represent the gun and target areas. Thus, the precise gun and target locations are not needed for the model to produce a CMM.
[5]The term "surface" actually refers to 10 m above the surface.
[6] The MET-TALL (as used by GTRAJ3) extends from the surface to 1500 meters' AGL.

For the RDAP analyses, the BFM-initializing RAOBs were taken 6, 3, or 1-1/2 hours before the firing. For the LUT analyses, all the initializing RAOBs were taken 5 hours before firing (with one exception explained in a later section). During the live fire exercises, RAOB data that were used by the gun crews for aiming were not available to ARL. It was necessary then to initialize the BFM with RAOBs taken by the YPG Met Team about 10 to 15 km from the gun locations. Although gun area RAOBs *were* available during the post-analysis phase, for the sake of consistency, all BFM initializations pertaining to this study were made with the YPG Met Team RAOBs. The *exact* location of the initializing RAOB is not important to the BFM, either to enhance or detract from its performance, as long as the RAOB site is relatively close to the forecast area in question. Therefore, it was inconsequential that YPG Met Team RAOBs were used to initialize the BFM, while gun area RAOBs were used for the actual aiming.

The BFM was then run to produce FCMMs that were valid at the firing time. For example, for a LUT firing scheduled at 1300 UTC[7], an 0800 UTC RAOB was released by the gun crews for preliminary aiming calculations, and an 0800 UTC YPG Met Team RAOB was used for the BFM initialization. The BFM then generated a 5-hour FCMM, valid at 1300 UTC.

4. The GTRAJ3 Trajectory Simulation Model

The RDAP and LUT series of SADARM artillery firings were simulated with the Armament Research, Development, and Engineering Center (ARDEC) Firing Tables Branch's general trajectory model Version 3 (GTRAJ3). This model is widely accepted in the artillery community as an accurate simulator of live artillery round trajectories. It uses applicable aerodynamic and ballistic factors and allows the operator to enter measured muzzle velocity, propellant temperature, gun and target elevation, azimuth/elevation aiming angles, and of course, a CMM and MET-TALL. Since all the gun-related factors were precisely known and input to GTRAJ3, the Met conditions were the only variable in the simulations.

GTRAJ3 uses the point mass equations of motion to simulate the trajectory of a projectile in flight, through user-defined time steps. It has a variety of integration and output options, but for this study, GTRAJ3 continued its integration from the gun area elevation to the target area elevation in 1-second time steps. Its coordinate system and output parameters are described in a later section.

No model could perfectly simulate artillery round trajectories, including GTRAJ3. However, it was considered accurate enough that it could be used as a discriminator between the two types of Met Messages. *The underlying assumption of this study is that if a perfect CMM (i.e., an exact representation of the atmosphere) could be obtained and entered in GTRAJ3, the simulated*

[7]Universal time coordinate, equal to local YPG time plus 7 hours.

impact point would hit very close to where the actual live round landed. It follows then that the most accurate simulation must have incorporated the most accurate CMM since all other factors were equal.

A final point about GTRAJ3 is that it is very similar to the battery computer system (BCS) software that is used by the gun crews to determine their aiming angles[8]. (The BCS software was not available for use in this study; consequently, GTRAJ3 was used instead.) Therefore, a GTRAJ3 simulation that incorporated the same RCMM as was used by the gun crews in the BCS was considered to be a reasonably good indicator of where the live rounds were actually targeted. (The significance of knowing approximately where the rounds were aimed is explained in a later section.) However, any reference herein to artillery aiming or aim points indicates a GTRAJ3 simulation *only* and does not imply the procedures used or the accuracies achieved by the SADARM gun crews.

5. Data Analysis Process

5.1 The Analytical Concept

Since the SADARM rounds experienced and responded to the true atmospheric conditions for each firing, the GTRAJ3 simulation that resulted in the closest impact to the actual RAID impact points was considered to be the one using Met data most representative of the "real atmosphere." (The other types of targeting factors mentioned previously, such as muzzle velocity, gun/target location, etc., were accounted for in this study since these values were precisely known and were entered in the GTRAJ3 simulations.) Thus, GTRAJ3 was run once with an RCMM and the specific input conditions for a particular firing (gun azimuth/elevation angles, propellant temperature, measured muzzle velocity, etc.). The trajectory model was then re-run with the identical input parameters but with an FCMM. The impact coordinates from both simulations were then compared to the actual RAID impact locations.

RCMMs were derived from balloon data taken from launches near the gun locations. These data were assumed to be valid at the apogee point, as is the current doctrine for artillery Met. The BFM-based CMMs and MET-TALLs were derived as described in Section 3.

5.2 RDAP Data Set Specifications

Table 1 summarizes the RDAP sequence of events on 25 January and 27 January 2000 for which Met data or firing/impact data were available. The RDAP data set afforded an excellent opportunity to explore the effects on the SADARM firing accuracy of having "stale"[9] RCMMs. In

[8]Based on personal communications with SADARM test personnel.
[9]Met data collected 3 or more hours before the actual firing time.

general, it is known that using "older" Met data for aiming artillery rounds will result in less accurate shots. The following data allowed the effects to be quantified (see Sections 6.1 and 6.2). As the table indicates, RAOBs were launched by the YPG Met Team as many as 6 hours before the first firing and then intermittently thereafter, throughout the mission day. Thus, we were able to run GTRAJ3 simulations for most of the shots using RCMMs that were 6, 3, and 1 hour(s) old (T-6, T-3, and T-1 hours).

Table 1. RDAP event times

	<25 JAN>			<27 JAN>	
Event Time (UTC)	**RAOB Site**	**TRN**[a]	**Event Time (UTC)**	**RAOB Site**	**TRN**
1200	GUN		1200	GUN	
1300	TGT		1300	TGT	
1500	GUN/TGT		1500	GUN/TGT	
1700	GUN/TGT		1700	GUN/TGT	
1728		18	1801		31
1832		19	1818		32
1900	GUN/TGT		1834		33
2026		20	1853		34
2045		21	1900	GUN/TGT	
2059		22	2100	GUN	
2100	GUN/TGT				
2300	TGT				
0007		23			
0023		24			
0041		25			

[a]TRN = tube round number

The terms "TGT" and "GUN" in the RAOB columns are somewhat inaccurate (particularly for the "GUN"). The "target area" RAOBs were launched by the Met Team at Tower M, about 6 km to the east-southeast of the targets at "impact area eve." Although not co-located, this site was considered to be reasonably representative of the actual target area. The location of the single Paladin gun used in the RDAP was at the YPG site named "SAD-20." The YPG Met site used for launching the aiming RAOBs was at "firing front road," about 25 km to the west of SAD-20. Since the rounds were fired in an easterly direction, the aiming RAOB was released about 35 km from the apogee point and almost 45 km from the target area (see Figure 1). Thus, the RDAP Met analyses also enabled us to evaluate the effects of spatial variations in RAOB data on SADARM firings. (Note that the gun crew used the RCMMs for *preliminary* aiming only. Inert "spotter" rounds were fired first, to precisely define the aiming solution. Consequently, the following live rounds impacted almost exactly where the gun crew intended. Thus, the spatial limitations of these RCMMs were evident only in the GTRAJ3 simulations and not in the results of the live firings.)

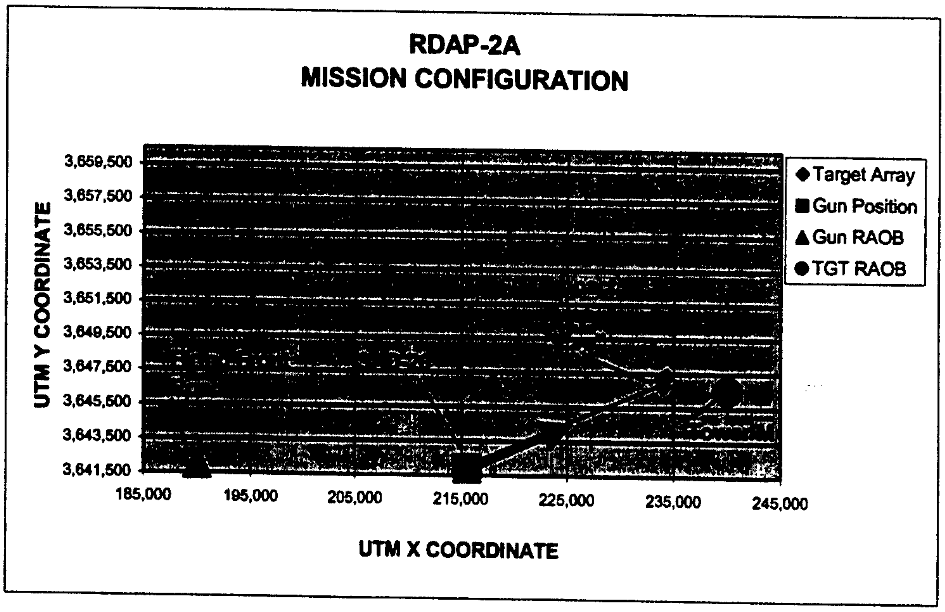


Figure 1. Mission configuration for the RDAP-2A.

ARDEC analysts provided the Microsoft Excel file containing the firing data for each round: azimuth and elevation angles, projectile weight, muzzle velocity, propellant temperature, etc., that were entered in the GTRAJ3.

5.3 LUT Data Set Specifications

Table 2 lists the LUT dates and times.

Table 2. LUT dates and firing times

MISSION	DATE	FIRING TIME (UTC)
LUT 1	11 APR 2000	1920
LUT 2	18 APR 2000	1310
LUT 3	25 APR 2000	2105
LUT 4	02 MAY 2000	1108

RAOB data were collected by the YPG Met Team 5 hours before (T-5), 1.5 hours before (T-1.5), and at the firing time (T-0) for each of the four LUT missions. As for the RDAP, these "target area" RAOBs were released from the Tower M site. During the LUT however, the guns were situated to the east of the target area (see Figure 2). Because Tower M was *between* the target array and the gun locations, its RAOB data were considered to be well representative of the trajectories of the rounds. A tactical Met unit was in the vicinity of the gun locations, from which aiming RCMMs were produced at T-1.5. Again, the ARDEC analysts provided the Excel file containing all pertinent firing data.

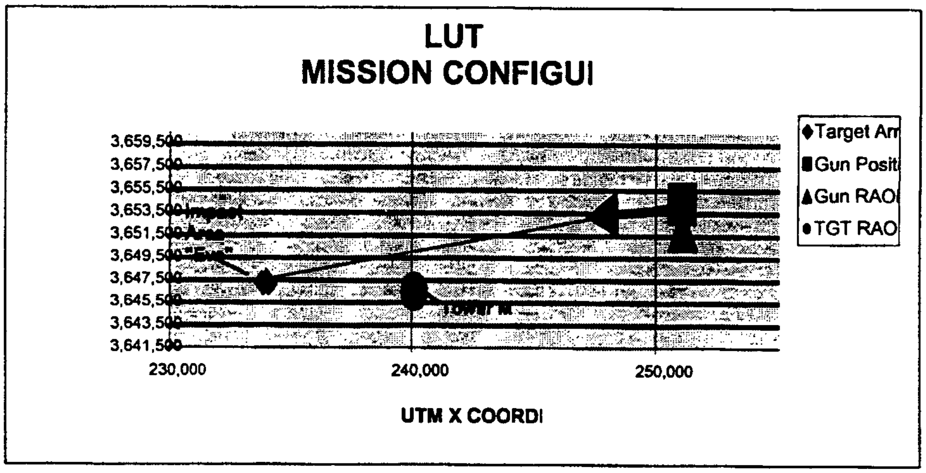


Figure 2. Mission configuration for the LUT.

5.4 Coordinate Transformations

The GTRAJ3 output is in an "E" coordinate system in which E1 is the down-range distance along the initial firing azimuth, E3 is the cross-range deflection perpendicular to the firing azimuth, and E2 is the height above a reference plane (in this study, above mean sea level). The RAID impact points are given in universal transverse mercator (UTM) coordinates. Thus, the E1/E3 distances from the gun(s) had to be converted to UTM coordinates for comparison against the RAID impacts. Figures 3 and 4 illustrate the trigonometry of the coordinate transformations for the RDAP and LUT, respectively. (Note that the "azimuth aim point" is not the target at which the gun crew was aiming. Instead, it is simply the approximate coordinate at which the cannon was pointed, the gun crew having accounted for the Coriolis force[10] and the estimated deflecting effects of the winds.)

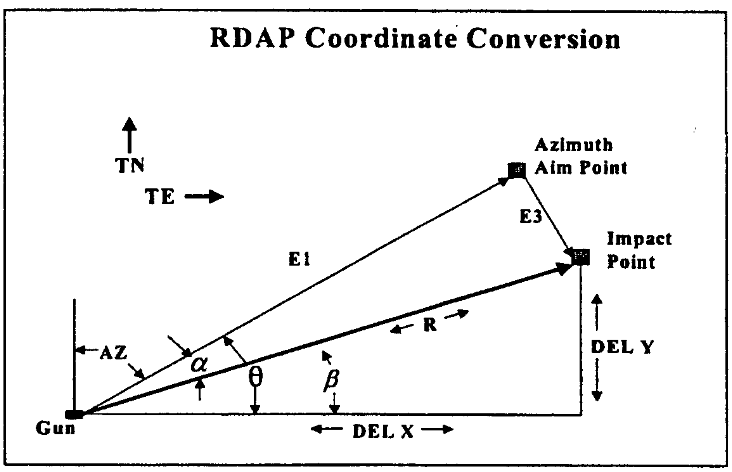


Figure 3. RDAP E1/E3 to UTM coordinate conversion.

[10]The "Coriolis force" is not a force in the usual sense. Rather, it is a term incorporated into trajectory calculations that "represents accelerations owing to the combined effects of rotation of the coordinates and motion of a particle relative to the rotating system" [4]. In this case, the "rotation of the coordinates" is the earth's rotation, and the "particle" is the SADARM round.

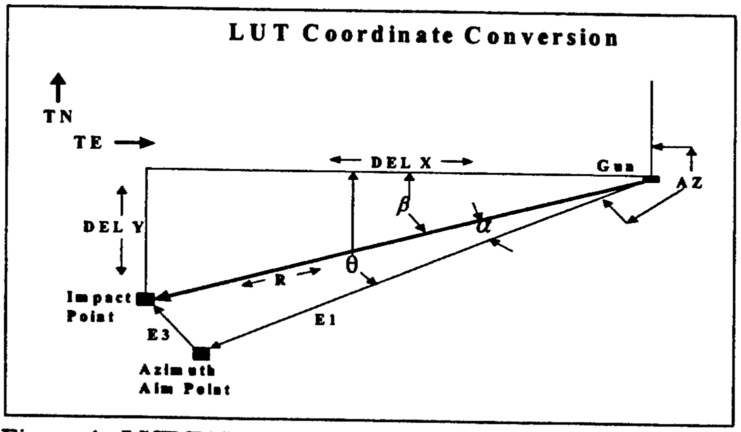


Figure 4. LUT E1/E3 to UTM coordinate conversion.

Here, "AZ" is the firing azimuth angle (relative to TN[11]). "R" is the range, gun to impact. The angle "θ" is the measure from TE[12] to the E1 line. Converting from AZ to θ is simply

$$\theta = 90 - AZ \tag{1}$$

The angle "α" is the angular change from the firing azimuth to the impact point (IP):

$$\alpha = TAN^{-1}\left(\frac{E3}{E1}\right) \tag{2}$$

The angle "β" is the angle from TE to the line connecting the gun and the IP and is found by

$$\beta = \theta - \alpha \tag{3}$$

The impact range "R" is simply

$$R = \sqrt{E1^2 + E3^2} \tag{4}$$

The "DEL X" and "DEL Y" values are then

$$\begin{aligned} \Delta X &= (R)\cos(\beta) \\ \Delta Y &= (R)\sin(\beta) \end{aligned} \tag{5}$$

Finally, the "X" and "Y" UTM coordinates of the impact are

$$\begin{aligned} X_{IP} &= X_{GUN} + \Delta X \\ Y_{IP} &= Y_{GUN} + \Delta Y \end{aligned} \tag{6}$$

[11] True north, which is assumed to be equivalent to the "Y" axis.
[12] True east, which is assumed to be equivalent to the "X" axis.

The equations for the LUT (see Figure 2) are identical except

$$\theta = 270 - AZ \tag{7}$$

$$X_{IP} = X_{GUN} - \Delta X$$

$$Y_{IP} = Y_{GUN} - \Delta Y \tag{8}$$

5.5 Mean Radial Miss Distances

To begin the analysis, X/Y plots of each firing were prepared showing the actual RAID IP. The plots also included target locations and the locations of the GTRAJ3 simulated impacts. For some of the plots, it was relatively easy to see which GTRAJ3 simulation (BFM- or RAOB-based CMM) came closer to the actual RAID IP(s). For other missions, however, this type of subjective evaluation was not readily evident. Figure 5 illustrates this point.

According to Figure 5, it appears that the RCMM simulation is closer to the RAID impact[13], but it is difficult to ascertain. With a simple Pythagorean Theorem calculation, the distance (called the radial miss distance or "RMD") from both simulated impact points to the RAID impact was determined. For example,

$$(RMD)_i = \left(\sqrt{(X_A - X_F)^2 + (Y_A - Y_F)^2}\right)_i \tag{9}$$

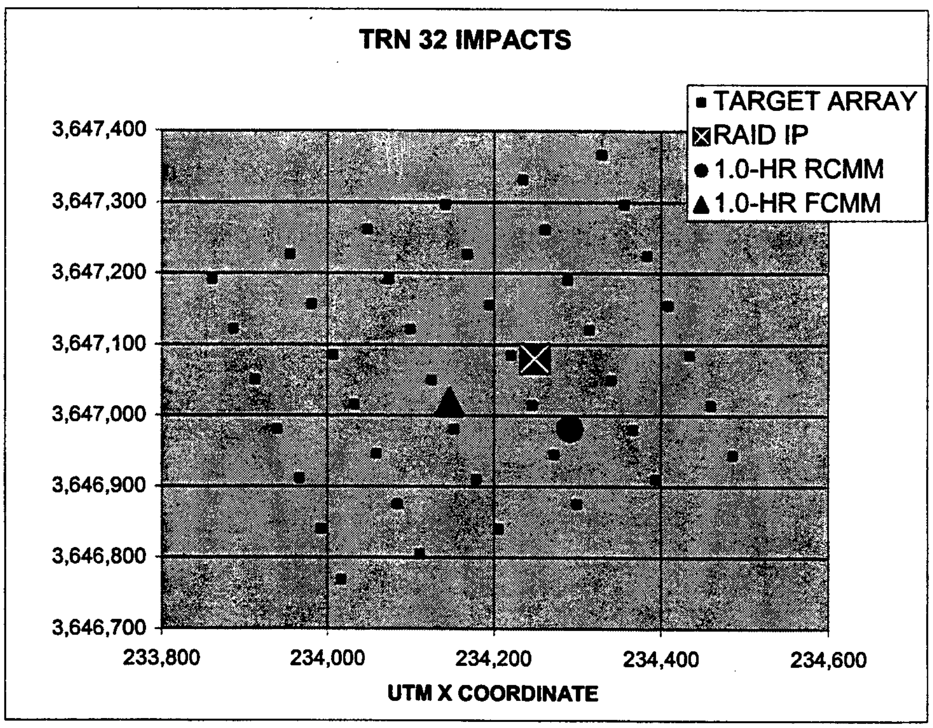


Figure 5. Mean radial miss distance illustration.

[13]This is actually the mid-point of the "fore" and "aft" RAID IPs. This mid-point was used in order to simplify the RDAP plots.

In Equation 9, the subscript "A" refers to the "actual" RAID impact coordinate and "F" refers to the simulated point using the FCMM, for the "ith" pair of actual and simulated impact coordinates.

The average of the "n" RMD's (in the case of the RDAP, when 12 firings were analyzed, n = 12), termed the "mean radial miss distance" (MRMD), was then calculated.

$$(MRMD)_F = \frac{\sum_{i=1}^{n} RMD_i}{n} \qquad (10)$$

The MRMD value was also found for the GTRAJ3 RCMM simulation. The MRMD values for BFM and RAOB simulations were then directly compared, as a quantitative indication of which Met produced the best results (i.e., closest to the actual trajectories of the SADARM rounds). The plots and the MRMD comparisons are discussed in following sections.

In the case of Figure 3, the RMD values were almost identical: 107 meters for RCMM-to-RAID IP and 119 meters FCMM-to-RAID IP.

6. Test Results

The following sections describe the scatter plot and MRMD results.

6.1 25 January

Eight rounds were fired on 25 January 2000. The simulations for TRN 20 are shown in Figure 6. Similar plots of the other seven rounds have been included in Appendix A. The four firings on 27 January were handled in a like fashion; only the plot for TRN 33 was included in Section 6.2. The plots for the other three rounds are in Appendix A. The tables containing the MRMD data include all the rounds.

The symbol labeled "ACT IP" is the actual RAID IP (mid-point of "fore" and "aft"). The point labeled "R-6HR" was the GTRAJ3 simulation using the 6-hour-old RCMM from the gun RAOB. The point labeled "F-6HR" was the GTRAJ3 simulated IP using the BFM 6-hour forecast FCMM. (The BFM was initialized with the 6-hour-old gun RAOB.) The simulated impacts for 3-hour and 1-hour old Met data input are correspondingly labeled. (It is not known why this particular round fell about 300 meters short of all the simulations. As indicated in Appendix A, the other simulations for 25 January were much closer to the actual impacts.) Figure 6 illustrates several points of interest. First, the simulated impacts were grouped in a fairly tight cluster. (Such was the case for the other firings that day as well.) This result is indicative of the rather

steady state wind conditions at YPG on 25 January 2000 at the levels above ~1800 meters' AGL (see Figure 7).

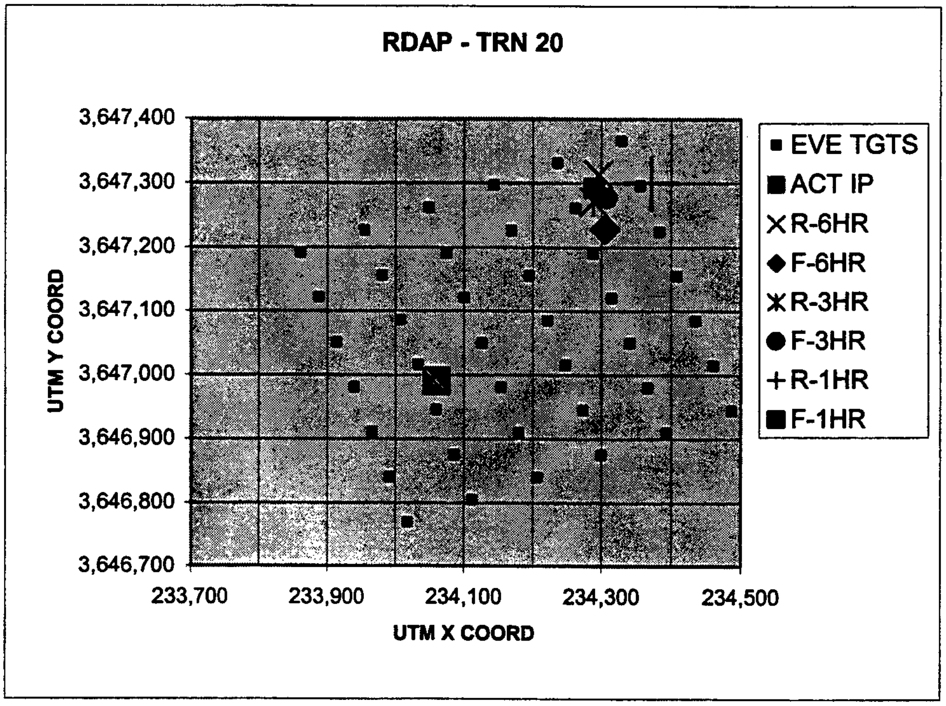


Figure 6. TRN 20 RAID and simulated impacts.

As Figure 7 depicts, the wind direction varied significantly in the lowest levels, but the wind speeds were relatively light.[14] Consequently, there was little effect on the outcome of the simulations. At the levels above 1800 meters' AGL, the directions and the speeds remained almost unchanged throughout the firing period.

Although the simulations for TRN 20 hit the farthest from the RAID, Figure 6 indicates that the FCMM simulations hit slightly closer to the RAID IP than their RCMM counterparts. Table 3 summarizes the RMD data from 25 January. (Because the firings for TRN 23, 24, and 25 occurred late in the day, no 1-hour-old RAOB was taken; consequently, no GTRAJ3 simulations were run.)

Table 3 indicates that for each time staleness category (6, 3, and 1 hour old), the MRMDs were smaller with BFM-forecast CMMs. Thus, the BFM yielded a more accurate representation of the atmosphere than did the RAOBs.

A final point to be noted from Figure 6 and Table 3 is that the "F-6HR" point landed closest to the RAID IP of any of the simulations (MRMD = 182 meters). This result indicates that a 6-hour BFM forecast of the CMM was the most accurate representation of the atmosphere, more so than shorter term forecasts that were initialized with more recent RAOBs (and more accurate than the

[14]Doubling the speeds, plotted in ms^{-1}, gives a close approximation to the value in knots.

RCMMs as well). In a general sense, the reason for this is that the model tends to take some time (in terms of length of forecast it is making) to properly "spin up" and then to converge on an accurate prediction. The specific factors that cause this phenomenon are complex and inter-related and are being investigated.

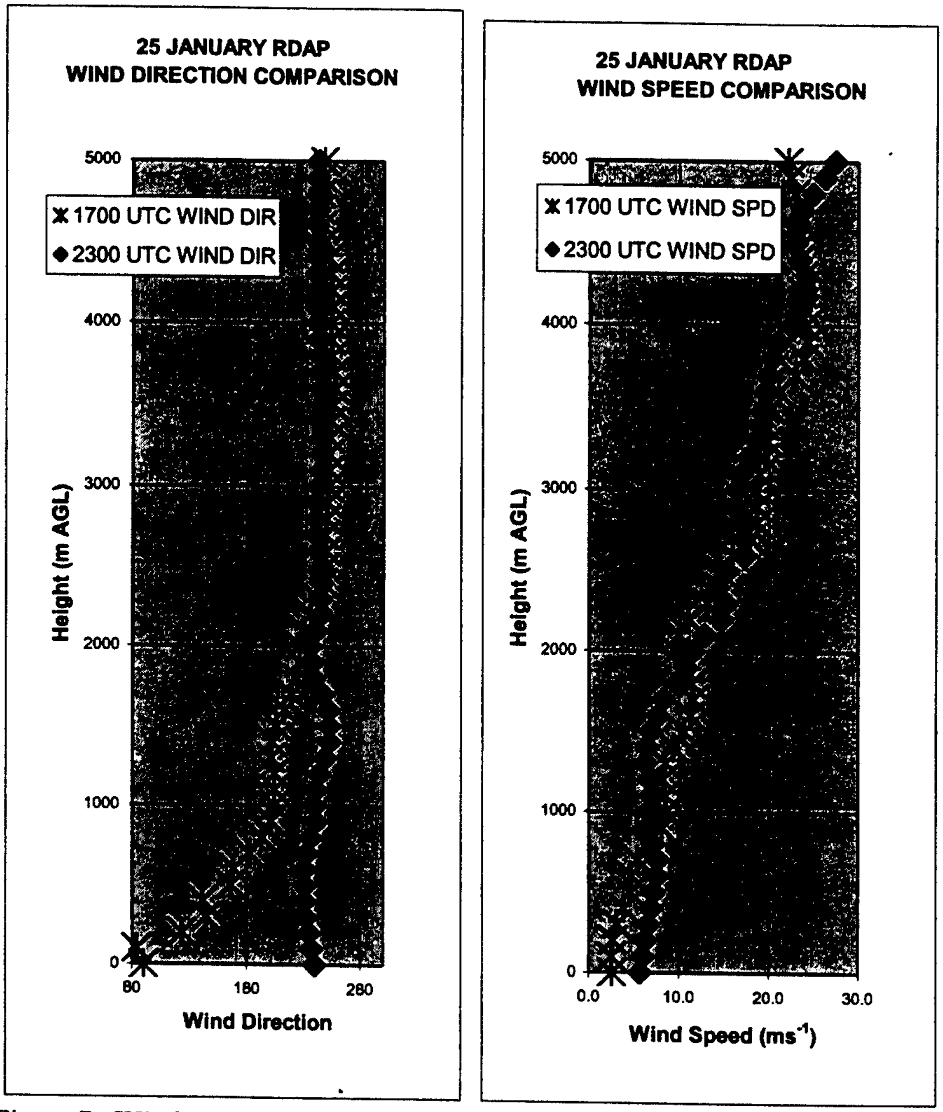


Figure 7. Wind comparisons for 25 January.

Table 3. 25 January RMD and MRMD values

TRN	[redacted]	R-3HR	F-3HR	R-1HR	F-1HR
18		306	235	266	279
19		271	190	229	202
20		362	380	440	380
21		198	201	230	218
22		66	84	124	110
23		212	175		
24		921	264		
25		292	244		
MRMD		256	222	258	238

6.2 27 January

Figure 8 portrays the impact simulations on the second day of the RDAP for TRN 33.

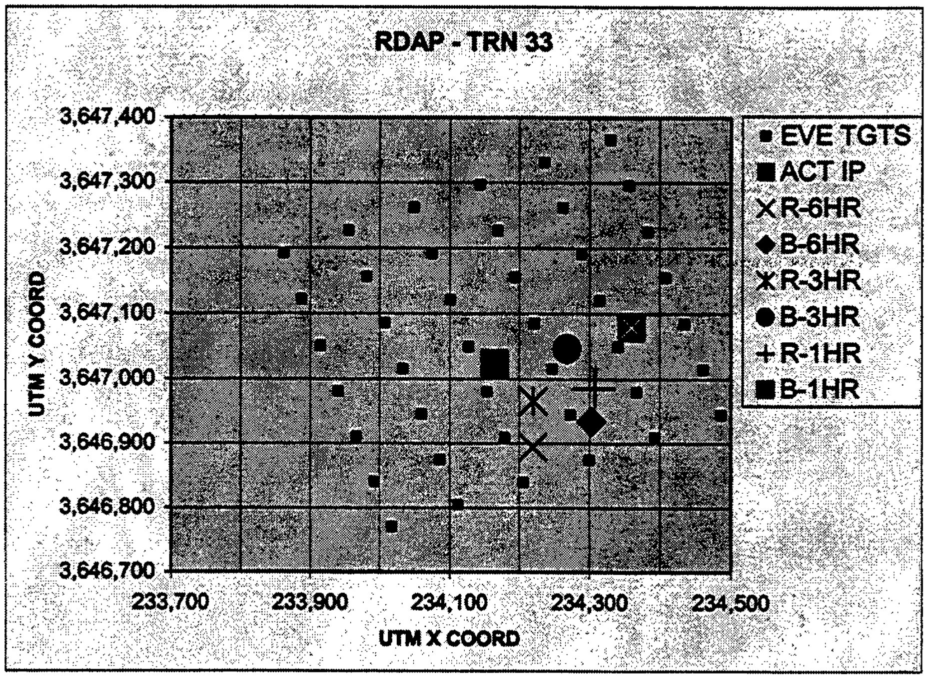


Figure 8. TRN 33 RAID and simulated impacts.

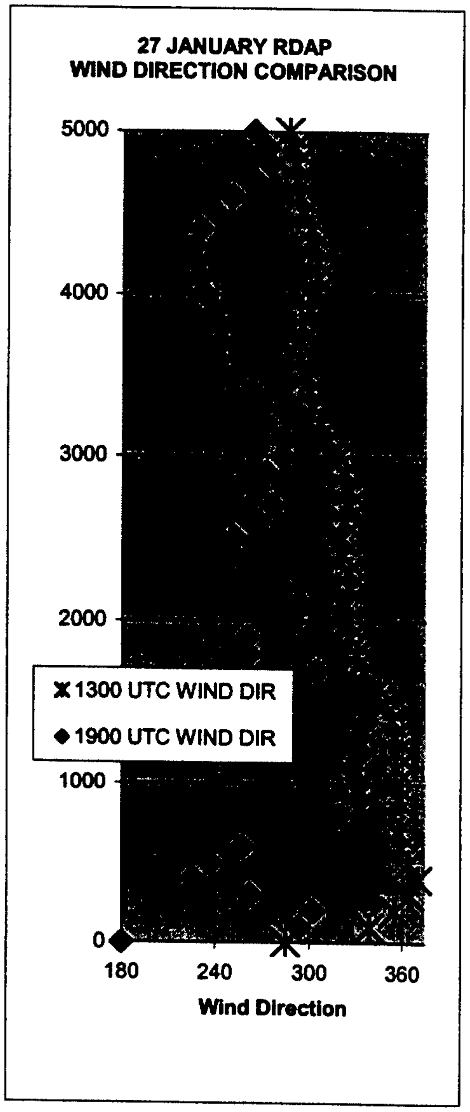
Of the four rounds fired on 27 January, the GTRAJ3 simulations for TRN 33 landed the *farthest* from the actual RAID IP. Since the BFM-based simulations for the other three rounds that day were even closer to the actual impact, it is clear then that the BFM did quite well in accurately representing the atmosphere.

The simulation IPs were somewhat more widely scattered on 27 January than for the first RDAP mission day. This finding suggests that more wind variability occurred during this test. Figure 9 depicts the wind comparisons for 27 January.

During the early morning, the wind came from a northerly or northwesterly direction. By noon, the direction at most levels had backed substantially around to the southwest. The speeds remained fairly steady except at the levels above 4000 meters' AGL (near the apogee point). There, the speeds increased 5 to 10 ms^{-1}.

Table 4 lists the RMD/MRMD values from 27 January.

The 6- and 3-hour forecasted FCMMs performed better than their RCMM counterparts in the GTRAJ3 simulations. Unlike on the first mission day, it was the *3-hour* BFM forecasts that were the most accurate on 27 January (MRMD = 48 meters). On this day, the 1-hour-old *RCMMs* outperformed their corresponding FCMMs (81 meters versus 141 meters overall MRMD).



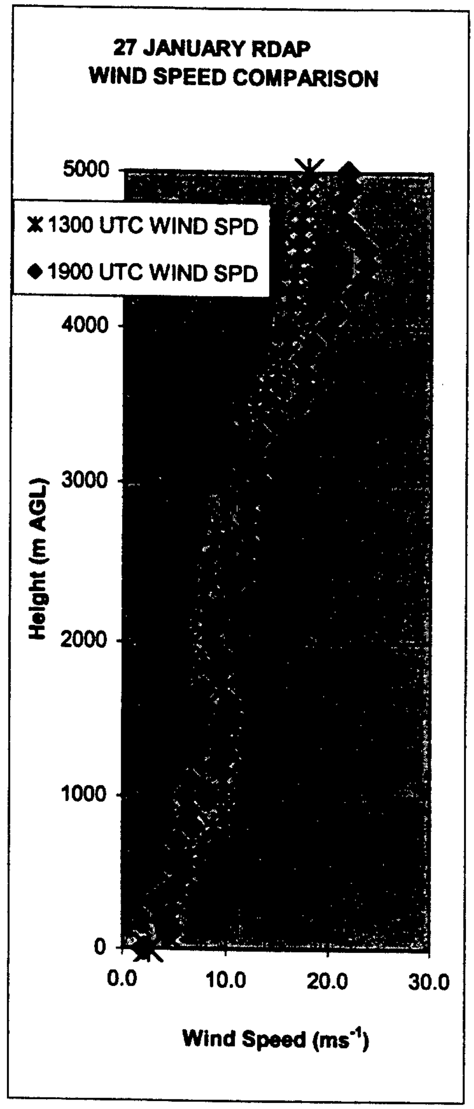


Figure 9. Wind comparisons for 27 January.

Table 4. 27 January RMD and MRMD values

[redacted]	R-3HR	B-3HR	[redacted]
[redacted]	78	47	[redacted]
[redacted]	127	38	[redacted]
[redacted]	181	97	[redacted]
[redacted]	106	12	[redacted]
[redacted]	123	48	[redacted]

6.3 LUT-1

Figure 10 shows the LUT target array and the simulated and actual IPs during LUT-1. (The Gun 3 firing was selected for plotting because it most clearly showed the results. Plots for the other five guns are included in Appendix B.)

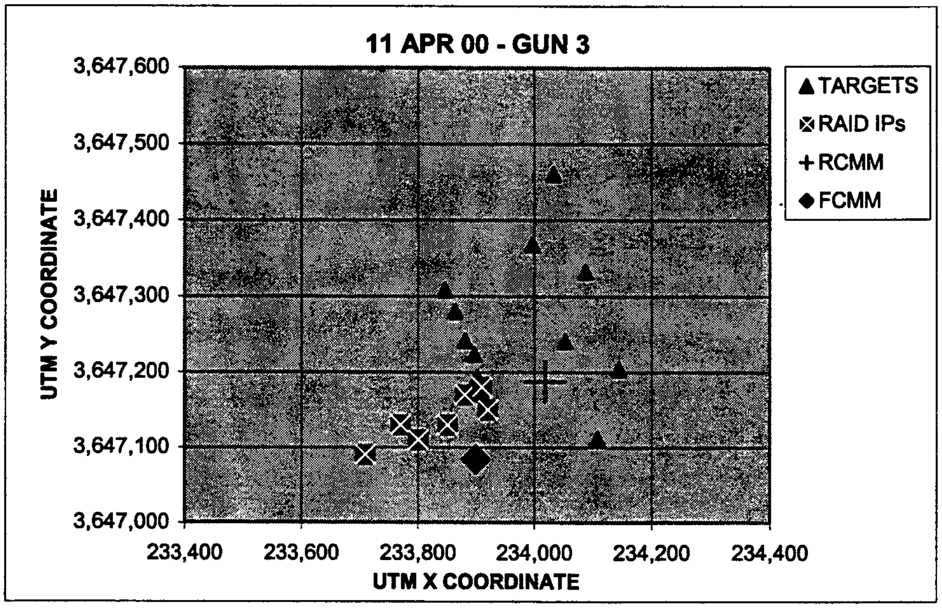


Figure 10. RAID and simulated impacts for LUT-1/Gun 3.

Using a 1.5-hour-old RCMM, the gun was aimed to impact within the target array (again, according to the GTRAJ3 simulation only, and not necessarily the gun crew's actual aim point). The large "+" sign indicates the predicted IP. However, the prevailing Met conditions at the time of the firing caused the eight rounds to fly a little long; several of them impacted anywhere from 100 to 200 meters beyond the western-most targets. The diamond symbol shows the simulated impact point with the 5-hour FCMM. The simulated coordinate is much closer to the scattering of RAID impacts. *This indicates that the BFM, while forecasting 5 hours into the future, more accurately represented the true atmospheric conditions at the time of the firing than did a RAOB that was only 1.5 hours old.* The simulations for most of the other five guns had similar results (see Table 5).

Table 5. MRMD values for LUT-1

	RCMM	FCMM	% IMPVMT
GUN-1	133	105	21
GUN-2	210	141	33
GUN-3	200	111	45
GUN-4	229	304	(33)
GUN-5	133	91	32
GUN-6	503	375	25
LUT-1 OVERALL	235	188	20

As the table indicates, only for Gun 4 was the RCMM more accurate than the FCMM. Averaging the six MRMD values together resulted in 188 meters for the FCMM versus 235 for the RCMM.

The "% IMPVMT" column indicates the percentage improvement in the MRMD values when one is changing from the RCMM to the FCMM in GTRAJ3. For example, with the Gun-3 firing, the MRMD value dropped from 200 to 111 meters—a 45% improvement. The percent "improvement" for Gun-4 was listed in parentheses since it was a negative value; i.e., the FCMM value was *greater* than its RCMM counterpart. Even after the negative Gun 4 result was included, there was still an overall 20% MRMD improvement when the BFM-based CMMs were used.

Because the aiming RCMM was only 1.5 hours old for each of the LUT missions, the issue of time staleness was not addressed as it was for the RDAP. However, the *spatial limitation* of the RAOB was demonstrated. Although the aiming RAOB was released near the gun locations, the physical configuration of the LUT highlighted the susceptibility of the RAOB balloon to wind drift. The gun batteries were situated at the extreme eastern edge of the YPG Kofa firing range (see Figure 11). The prevailing winds were inclined to carry the balloons away from the test facility (indicated by the arrow), rendering their RCMMs less and less representative of the SADARM trajectories as the balloons ascended. Apparently, this was the case during LUT-1, during which the winds at most of the levels came from the northwest to north.

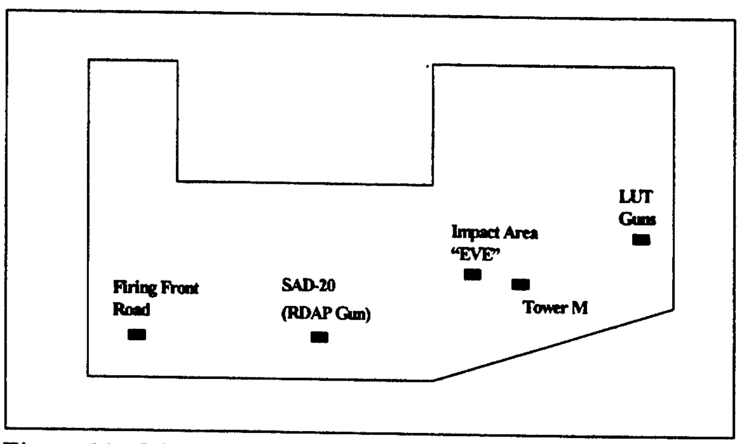
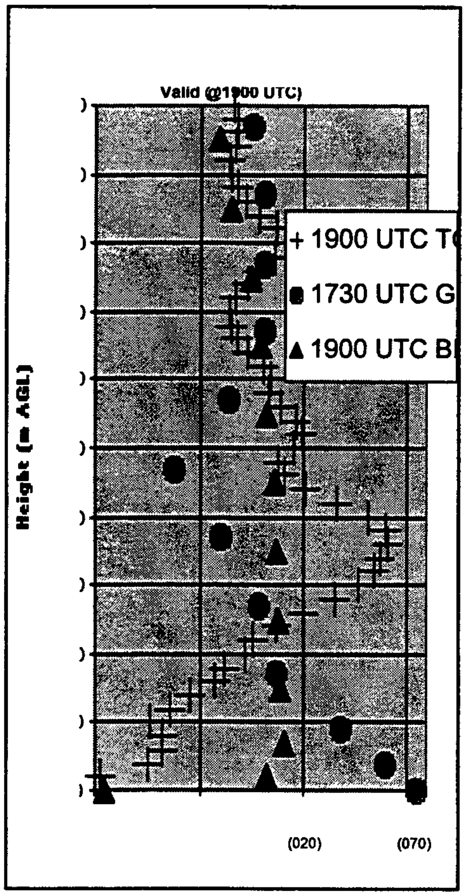


Figure 11. Diagram of the YPG Kofa firing range.

Figure 12 indicates that the FCMM (triangle symbols) tended to be closer to the 1900 UTC wind directions (the "+" symbols) at most of the levels than were the T-1.5-hr RCMM (the solid circle symbols). The BFM did, however, over-predict the speed of the wind at heights above 500 meters' AGL.



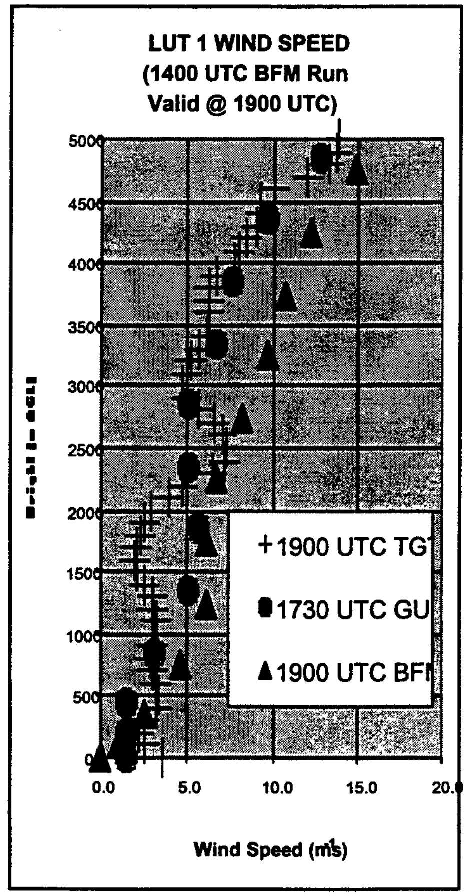
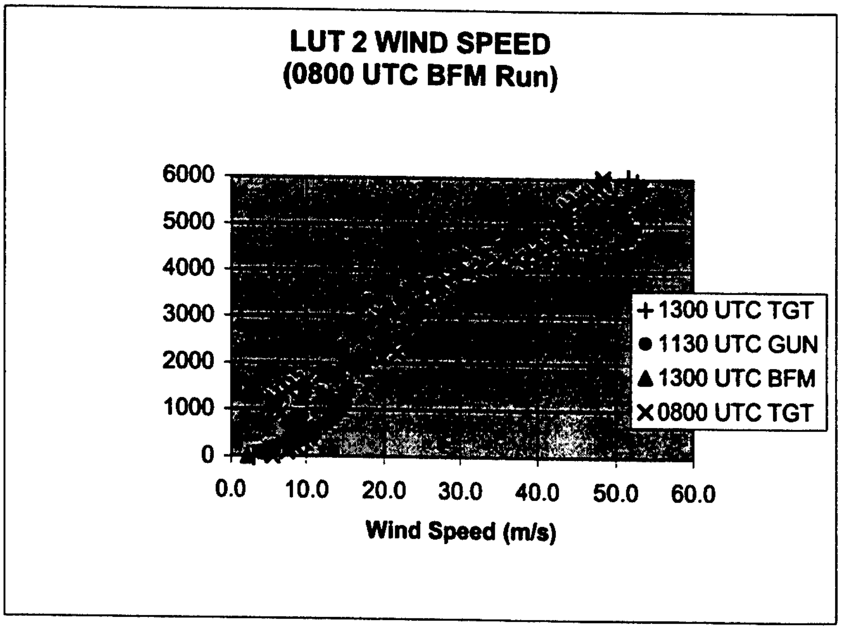


Figure 12. Wind comparisons for LUT-1.

6.4 LUT-2

During LUT-2, a powerful disturbance in the upper atmosphere caused very strong winds (exceeding 50 ms^{-1} near the apogee of the rounds) that significantly changed direction shortly before the firing. Figure 13 illustrates the wind conditions that night. The "X" symbols (labeled "0800 UTC TGT") indicate the winds as measured from the Tower M RAOB site. The "+" symbols show the Tower M winds 5 hours later, at T-0. These plots point out that the speeds at many levels increased during that 5-hour time span, and the wind direction changed substantially. The solid circles are the RCMM direction and speed plots. (This was the 1130 UTC RCMM used by the gun crews for aiming.) Finally, the solid triangles indicate the BFM-predicted FCMM that was valid at T-0.



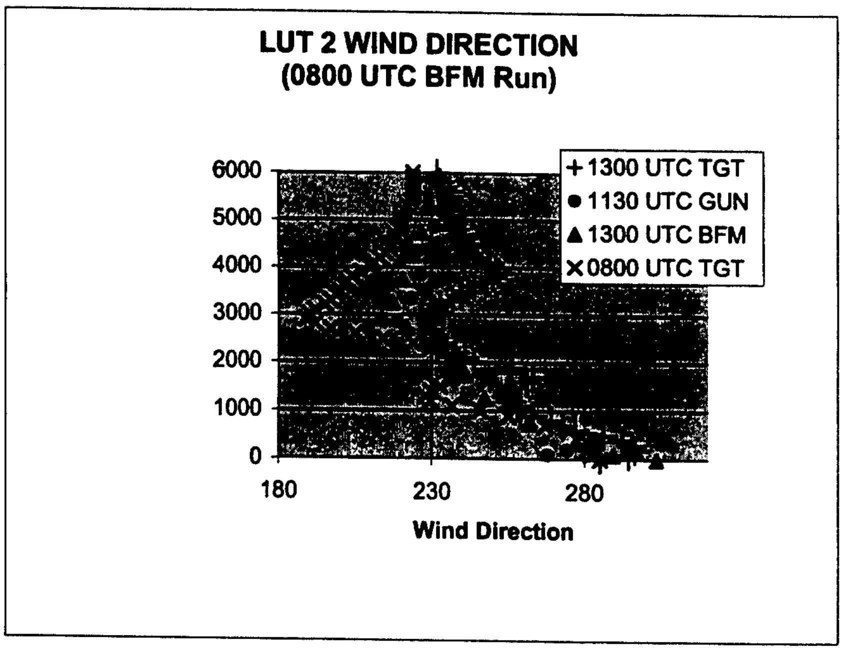


Figure 13. Wind comparisons for LUT-2.

As indicated by Figure 13, neither the 1130 UTC gun RAOB nor the BFM prediction matched the 1300 UTC target area winds extremely well. Given such strong winds at most of the trajectory levels, these inaccuracies affected GTRAJ3 significantly. Figure 14 depicts the results of the quickly changing wind situation during the 18 April firings.

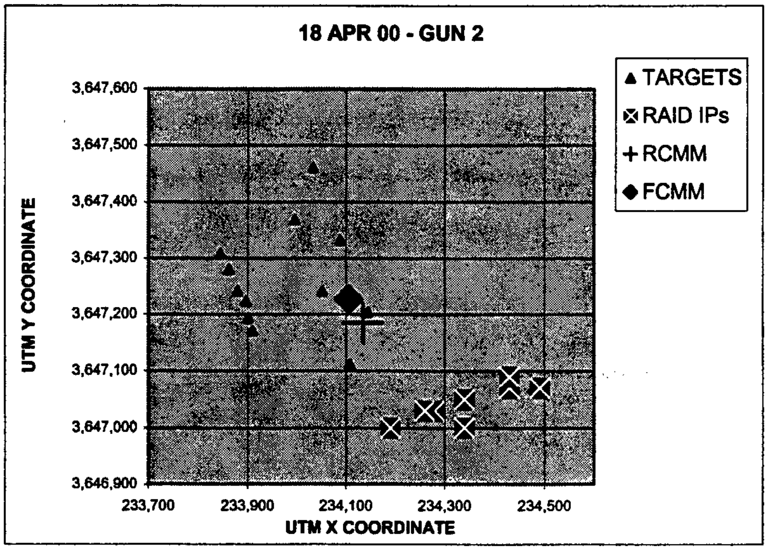


Figure 14. RAID and simulated impacts for LUT-2/Gun 2 (T-5 hr BFM initialization).

In this case, the RCMM (1.5 hours old) was a slightly more accurate representation of the firing conditions than the 5-hour predicted FCMM. As the plot indicates, the RCMM simulation impacted about 50 meters closer to the RAID IPs than did the FCMM counterpart. Such was the case for the firings from the other five guns. However, neither simulation did well, considering that the RAID IPs were anywhere from 245 to 324 meters to the south and east. Table 6 lists the MRMD values. The "%IMPVMT" values were all negative, which simply indicates that each FCMM simulation landed farther away from the RAID IPs than did the RCMM counterpart.

Table 6. MRMD values for LUT-2 (T-5 hr BFM initialization)

	RCMM	FCMM	% IMPVMT
GUN-1	257	308	(20)
GUN-2	266	313	(18)
GUN-3	283	324	(14)
GUN-4	253	302	(19)
GUN-5	245	295	(20)
GUN-6	260	292	(12)
LUT-2 OVERALL	261	306	(17)

Given the very dynamic weather situation of 18 April, we were curious whether the BFM would perform better if initialized with a more recent RAOB, namely, the T-1.5-hour data set. The results were encouraging and are shown in Figure 15 and Table 7.

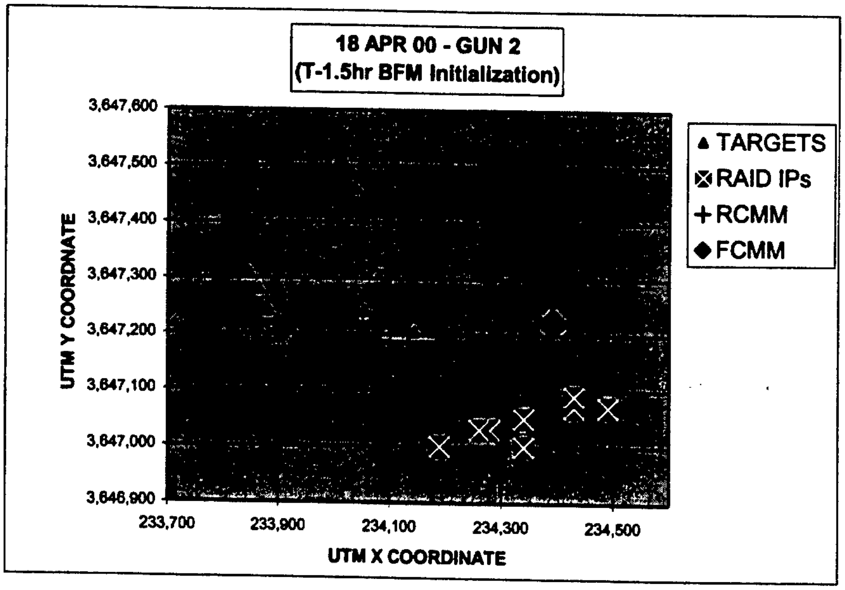


Figure 15. RAID and simulated impacts for LUT-2/Gun 2 (T-1.5 hr BFM initialization).

The FCMM-simulated IP for Gun 2 shifted much closer to the RAID IPs. The same shift occurred for the other five simulations as well. Table 7 summarizes the MRMDs.

Table 7. MRMD values for LUT-2 (T-1.5 hr BFM initialization)

	RCMM	FCMM	% IMPVMT
GUN-1	257	269	(5)
GUN-2	266	204	23
GUN-3	283	196	31
GUN-4	253	290	(15)
GUN-5	245	254	(4)
GUN-6	260	185	29
LUT-2 OVERALL	261	233	11

We found that initializing the BFM with a more recent RAOB tipped the scales in favor of the FCMM (overall, 233 meters versus 261 meters—an 11% improvement). Although not an everyday occurrence, high wind conditions similar to 18 April 2000 are fairly common during the winter and spring at middle and high latitudes in the northern hemisphere. As was demonstrated by the LUT-2 RAID IPs, strong and shifting winds can have a significant effect on artillery targeting accuracy.

6.5 LUT-3

The GTRAJ3 simulations proved to be a "mixed bag" for the LUT-3 analyses. Figure 16 shows the RCMM simulation to be closer to three of the RAID IPs, while the FCMM-based simulation was closer to the remainder.

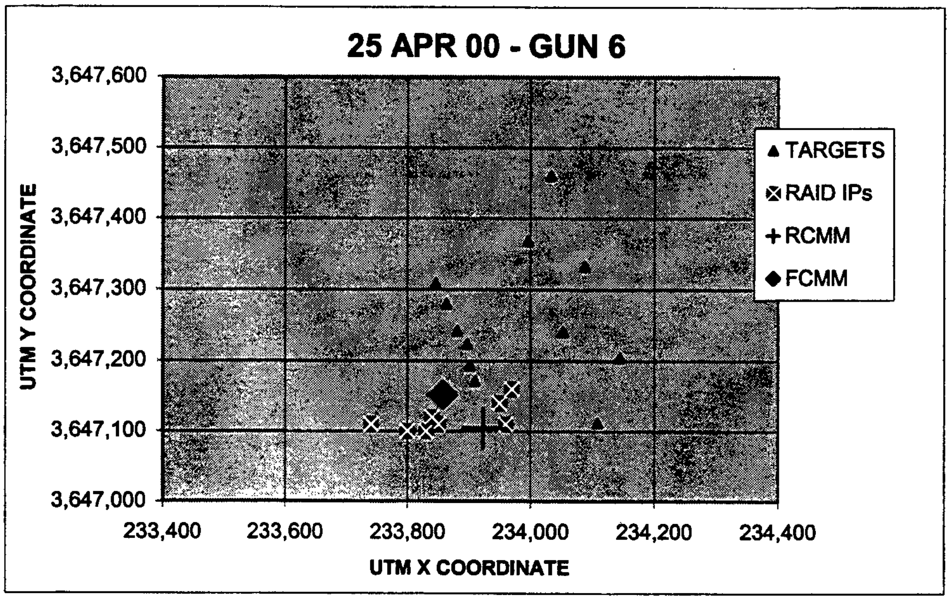


Figure 16. RAID and simulated impacts for LUT-3/Gun 6.

Table 8 lists the MRMD values for LUT-3.

Table 8. MRMD values for LUT-3

	RCMM	FCMM	% IMPVMT
GUN-1	86	112	(30)
GUN-2	190	269	(42)
GUN-3	336	252	25
GUN-4	186	108	42
GUN-5	181	248	(37)
GUN-6	89	82	8
LUT-3 OVERALL	178	178	0

The simulated firings from Guns 3, 4, and 6 resulted in lower MRMD values with the FCMM. The opposite was true for Guns 1, 2, and 5. Coincidentally, the overall average MRMD for both types of CMMs was 178 meters.

6.6 LUT-4

The BFM did an excellent job of accurately predicting the atmospheric conditions during LUT-4. Figure 17 shows the impacts from Gun 1. Here, the actual RAID impacts fell within the northern

portion of the target array. The GTRAJ3 simulation using the 1.5-hour stale RCMM fell short of the target area. The simulation that incorporated the 5-hour forecast FCMM hit within the target area and closer to the RAID IPs.

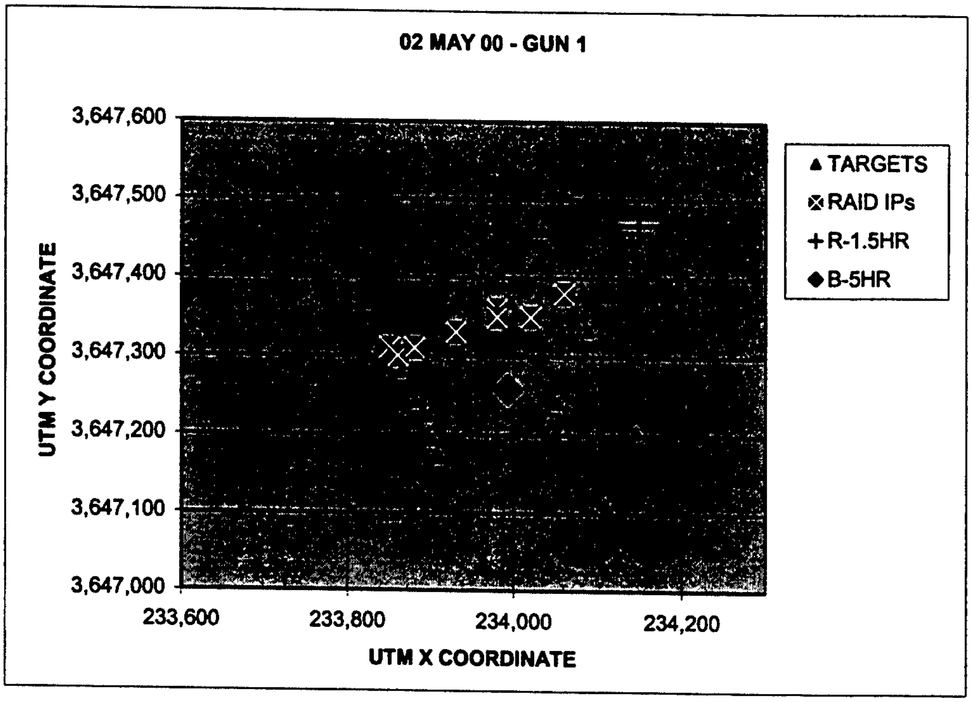


Figure 17. Actual/simulated impacts for LUT-4/Gun 1.

Table 9 summarizes the LUT-4 results.

Table 9. MRMD values for LUT-4

	RCMM	FCMM	% IMPVMT
GUN-1	243	118	51
GUN-2	163	183	(12)
GUN-3	265	176	34
GUN-4	266	151	43
GUN-5	308	176	43
GUN-6	299	157	47
LUT-4 OVERALL	257	160	38

The MRMD values for the FCMM simulations were smaller than their RCMM counterparts for five of the six guns. Overall, the values for the FCMM averaged almost 100 meters closer than for the RCMM (160 versus 257 meters)—a 38% improvement). Clearly, the BFM-based CMMs were the more accurate representations of the atmosphere during LUT-4.

7. Summary and Conclusions

The MRMD values resulting from GTRAJ3 simulations of the RDAP and LUT firings clearly showed the advantage of using BFM-based CMMs. Table 10 encapsulates the overall findings.

Table 10. Summary of MRMD values

	RCMM[a]	FCMM (LUT-2, T-5 BFM	FCMM (LUT-2, T-1.5 BFM
25 January	263	214	214
27 January	125	104	104
LUT-1	235	188	188
LUT-2 (T-5 init)	261	306	
[redacted]			
LUT-3	178	178	178
LUT-4	257	160	160
OVERALL	**220**	**192**	**180**

[a]The RDAP data for MRMD are overall averages of the 6-, 3-, and 1-hour values.

For the RCMMs, the overall average MRMD for the six data sets was 220 meters. When we included the LUT-2 result for which the BFM was initialized with a 5-hour-old RAOB (306 meters), the FCMM overall MRMD was 192 meters. When the LUT-2 result for which the BFM was initialized was substituted by a 1.5-hour-old RAOB instead (233 meters), the overall MRMD dropped to 180 meters.

Our conclusion from these MRMD results is that the BFM-based CMMs provided a more accurate representation of the "true" atmosphere than did their RAOB-based counterparts. With a few exceptions, this finding held true, regardless of the "staleness" of the RCMM or how close to the guns it originated.

8. Recommendations

An important step toward applying modeled CMMs on the battlefield will be to move from the simulation realm to the live fire arena. Because of the positive results of this study, we recommend that BFM-forecast Met messages be used in place of the standard RAOB data, for a live fire exercise. This "proof of concept" (POC) could be in conjunction with SADARM or other types of field artillery exercises, as available. The POC would be a crucial first step toward the eventual replacement on the battlefield of RAOB-based aiming messages with more accurate modeled data.

References

1. Jameson, T, S. A. Luces, and D. Knapp, *Comparisons of Ballistic Trajectory Simulations Using Artillery Meteorological Messages Derived from Local Balloon Data and Battlescale Forecast Model Data for the 1998 SADARM IOT&E Firings*, ARL-TR-1018, U.S. Army Research Laboratory, White Sands Missile Range, NM, 2001.

2. Yamada, T., and S. Bunker, "Numerical Study of Nocturnal Drainage Flows with Strong Wind and Temperature Gradients," *Journal of Applied Meteorology,* Vol. 28, pp. 54 5-554, 1989.

3. Henmi, T., and R.E. Dumais, *Description of the Battlescale Forecast Model*, ARL-TR-1032, U.S. Army Research Laboratory, White Sands Missile Range, NM, 1996.

4. Hess, S.L., *Introduction to Theoretical Meteorology*, p. 164. Holt, Rinehart, and Winston, New York, 1959.

Appendix A: SADARM Live and Simulated Impacts for the RDAP

General Discussion

This appendix contains Met analyses of data collected during the SADARM RDAP artillery firings that occurred during January 2000 at Yuma Proving Ground, Arizona. RAID IPs (which closely represent the impacts of the live munitions) were compared against predicted IPs derived from a trajectory simulation program. Two types of Met data were entered in the simulator (measured RAOBs and data generated by a Met forecast model named the BFM). The Met data were in a format called CMMs. The RAOB-based CMMs were labeled RCMMs, and those BFM-based CMMs were labeled forecast CMMs or FCMMs. The figures in this appendix are plots from the TRNs that were not included in the main text.

On these plots, the symbol labeled "ACT IP" is the actual RAID IP, and the array of 40+ targets (tracked vehicle shells containing gasoline generators for infrared heat sources) is shown by the small squares. The point labeled "R-6HR" was the simulated IP that used the 6-hour-old RCMM from the gun RAOB. The point labeled "F-6HR" was the simulated IP that used the BFM 6-hour forecast FCMM. (The BFM was initialized with the 6-hour-old gun RAOB). The simulated impacts for 3- and 1-hour-old Met data input are correspondingly labeled. Plots for TRNs 18, 19, and 21 through 25 are from 25 January 2000. Plots for TRNs 31, 32, and 34 are from 27 January 2000.

The axes are X/Y coordinates in the UTM geographical coordinate system.

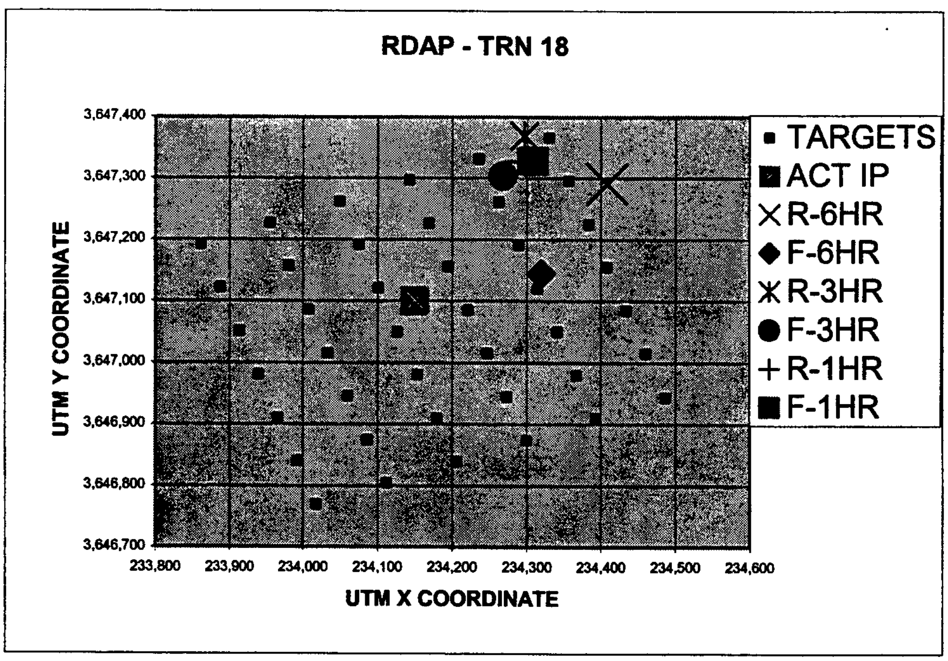


Figure A-1. TRN 18 RAID and simulated impacts.

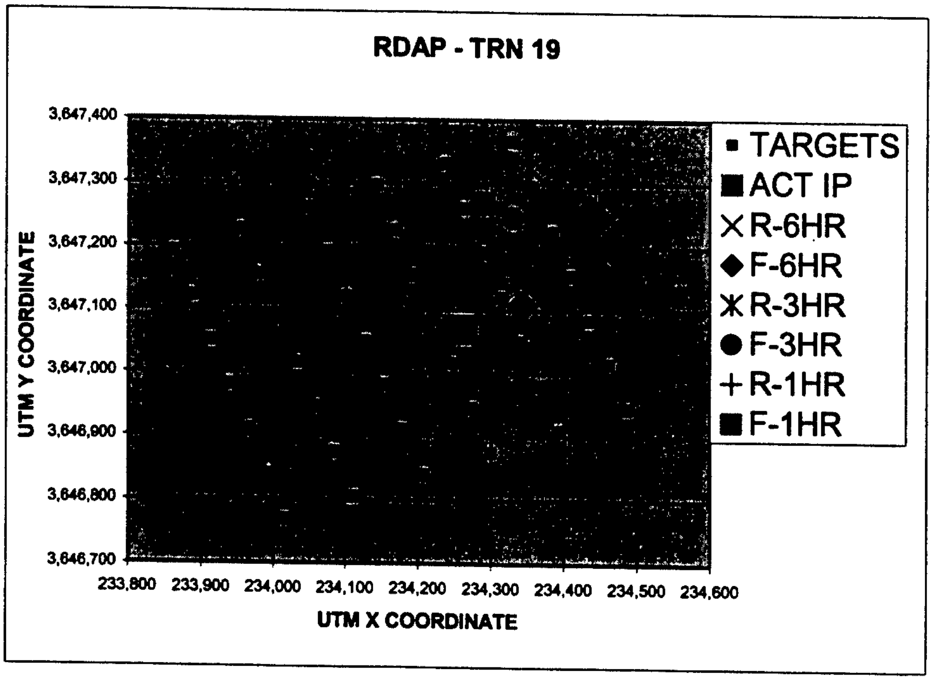


Figure A-2. TRN 19 RAID and simulated impacts.

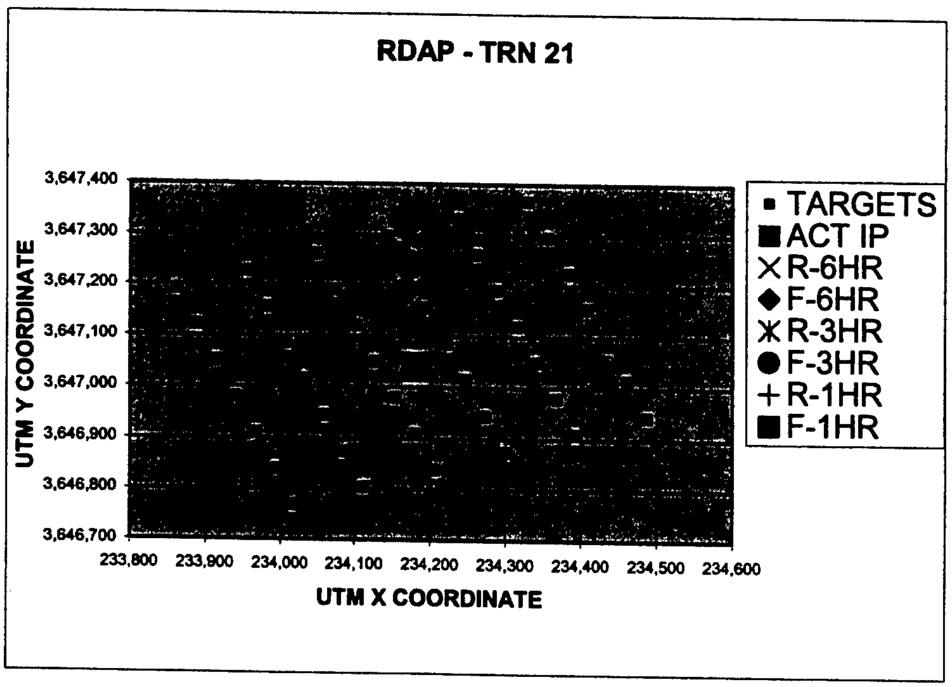


Figure A-3. TRN 21 RAID and simulated impacts.

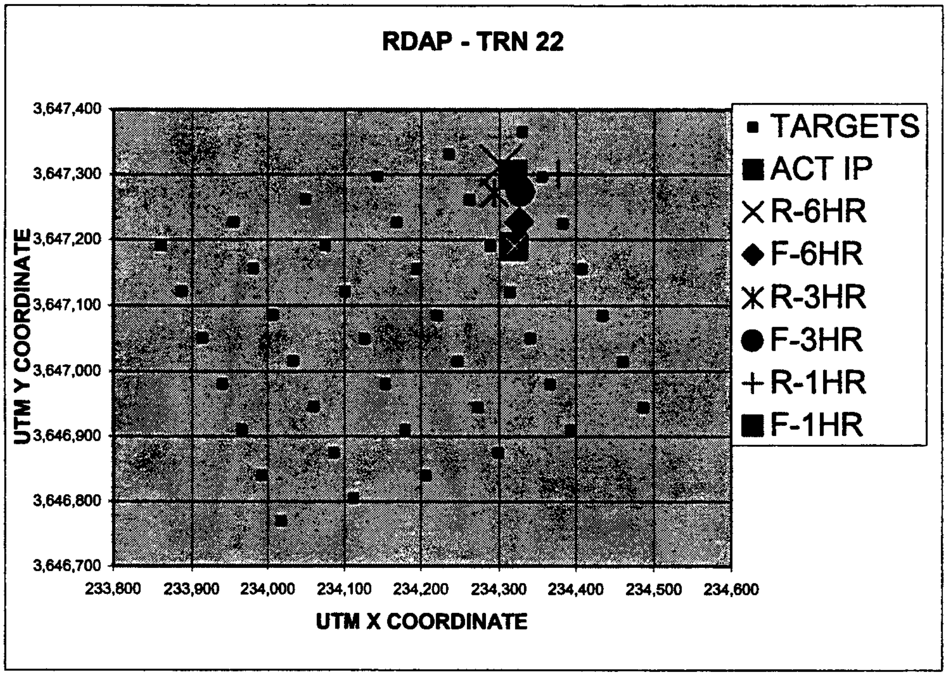


Figure A-4. TRN 22 RAID and simulated impacts.

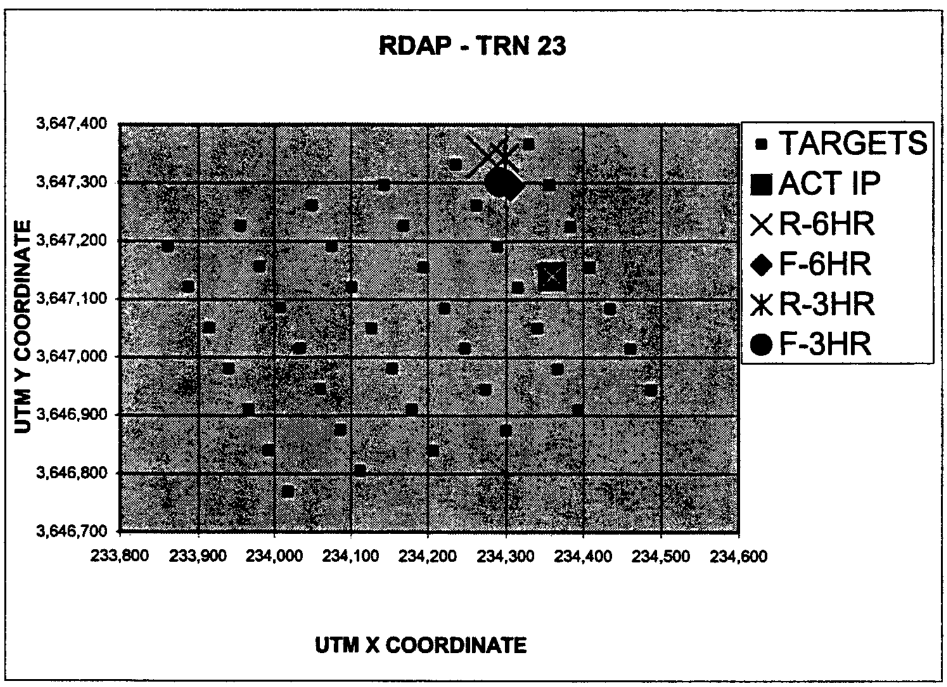


Figure A-5. TRN 23 RAID and simulated impacts.

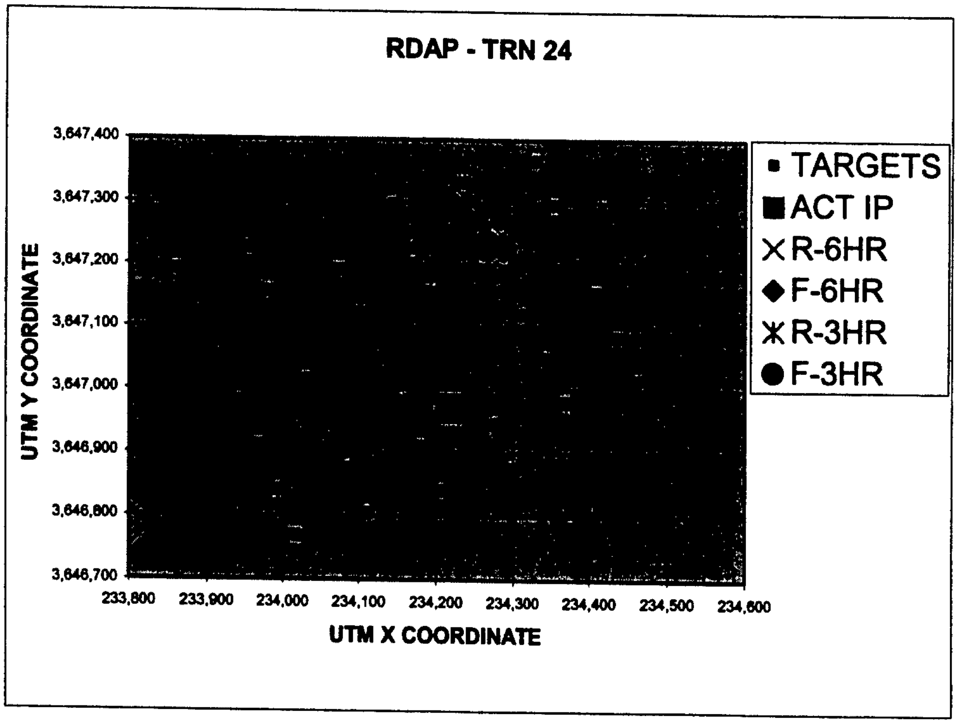


Figure A-6. TRN 24 RAID and simulated impacts.

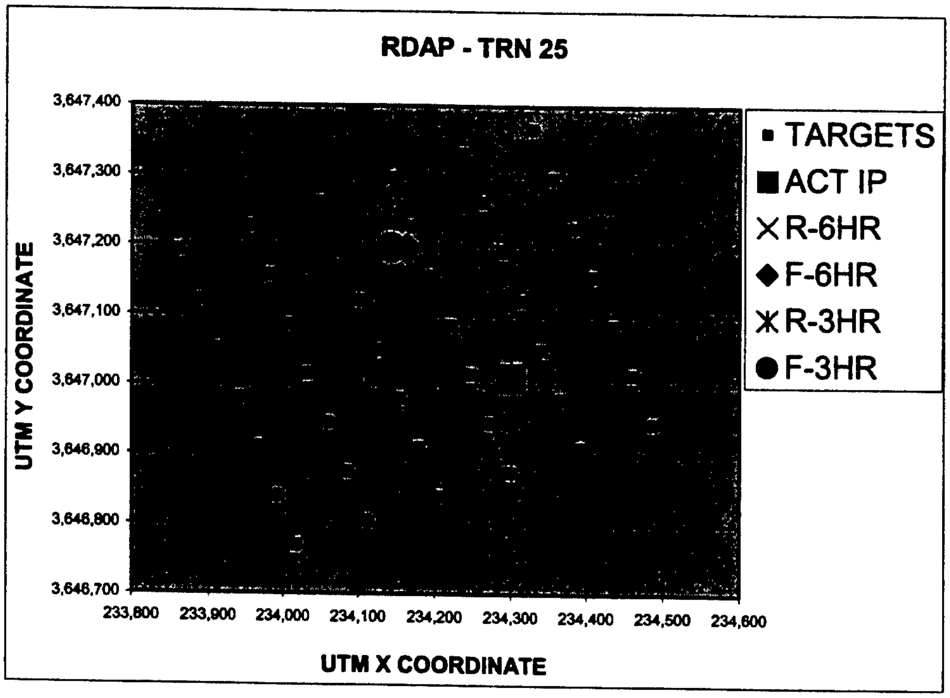


Figure A-7. TRN 25 RAID and simulated impacts.

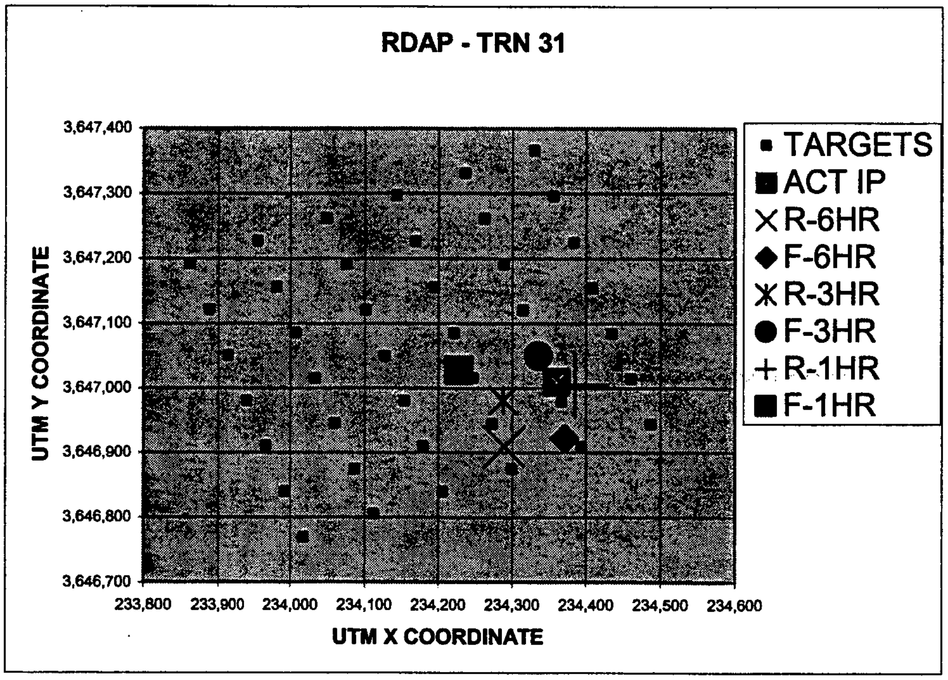


Figure A-8. TRN 31 RAID and simulated impacts.

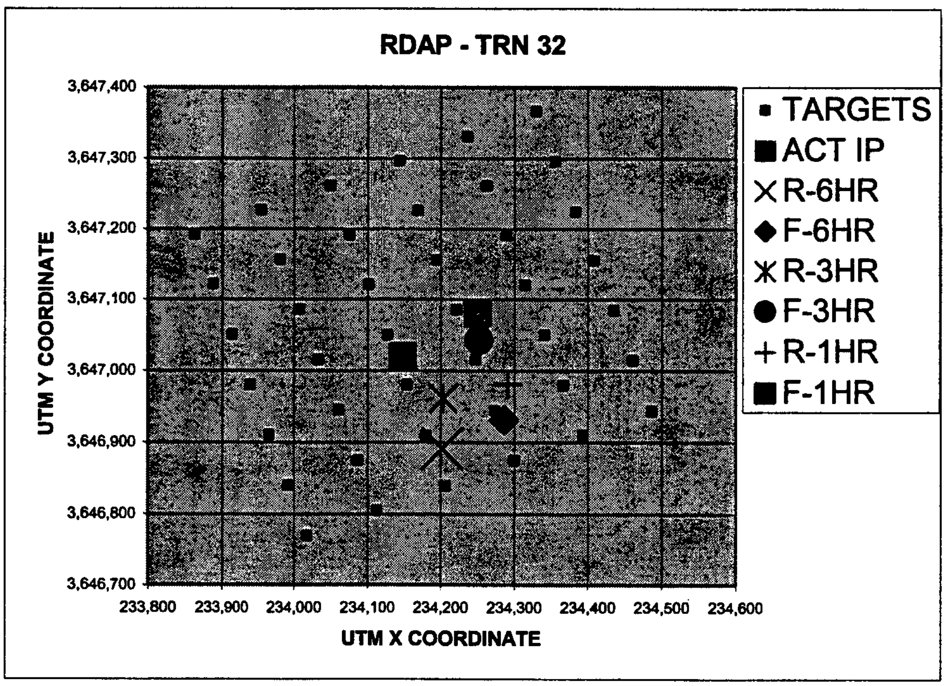


Figure A-9. TRN 32 RAID and simulated impacts.

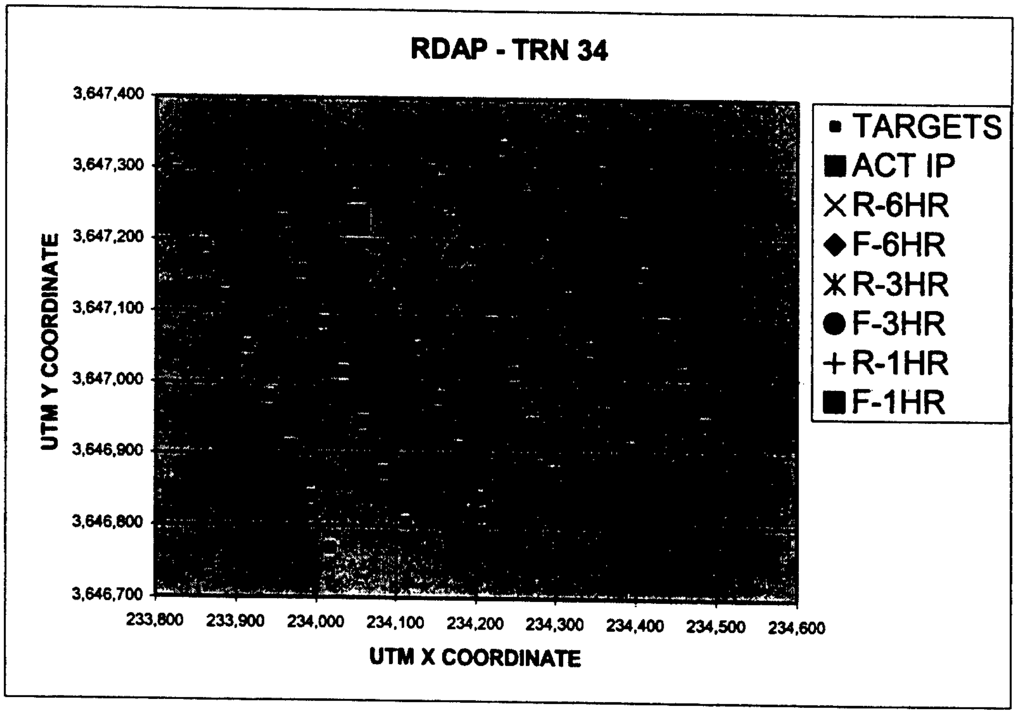


Figure A-10. TRN 34 RAID and simulated impacts.

Appendix B: SADARM Live and Simulated Impacts for the LUT

General Discussion

This appendix contains Met analyses of data collected during the SADARM LUT artillery firings that occurred during April and May 2000 at Yuma Proving Ground, Arizona. RAID IPs (which closely represent the impacts of the live munitions) were compared against predicted IPs derived from a trajectory simulation program. Two types of Met data were input to the simulator (measured RAOBs and data generated by a Met forecast model named the BFM). The Met data were in a format called CMMs. The RAOB-based CMMs were labeled RCMMs, and those BFM-based CMMs were labeled FCMMs. The figures in this appendix are plots from the other participating guns (those not shown in the main body of the text) for the four LUT mission days.

On these plots, the symbols labeled "RAID IPs" are the scattering of approximately eight RAID Ips, and the array of 12 targets (vehicles and a tent) is shown by the small triangles. The point labeled "R-1.5HR" was the simulated IP that used the 1.5-hour-old RCMM from the gun RAOB. The point labeled "F-5HR" was the simulated IP that used the BFM 5-hour forecast FCMM. (The BFM was initialized with the 5-hour-old gun RAOB.)

The axes are X/Y coordinates in the UTM geographical coordinate system.

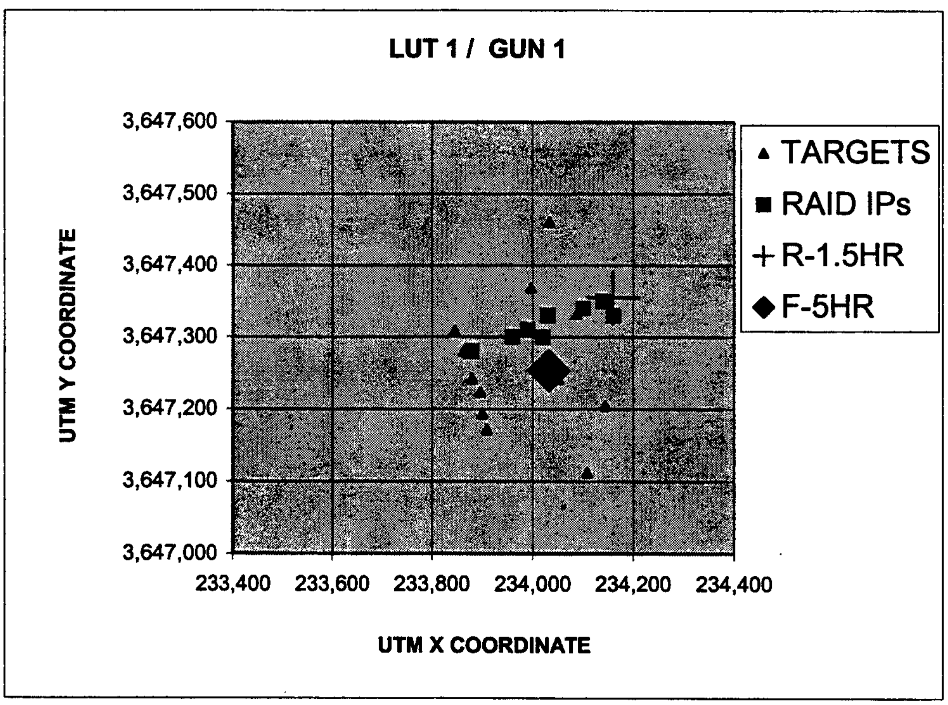


Figure B-1. RAID and simulated impacts for LUT-1/Gun 1.

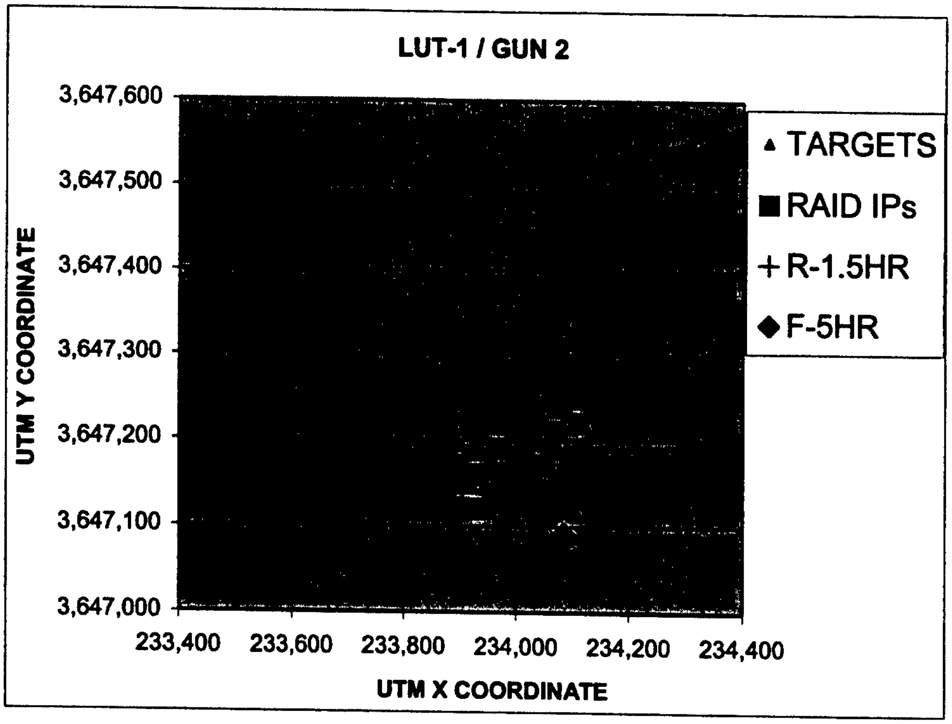


Figure B-2. RAID and simulated impacts for LUT-1/Gun 2

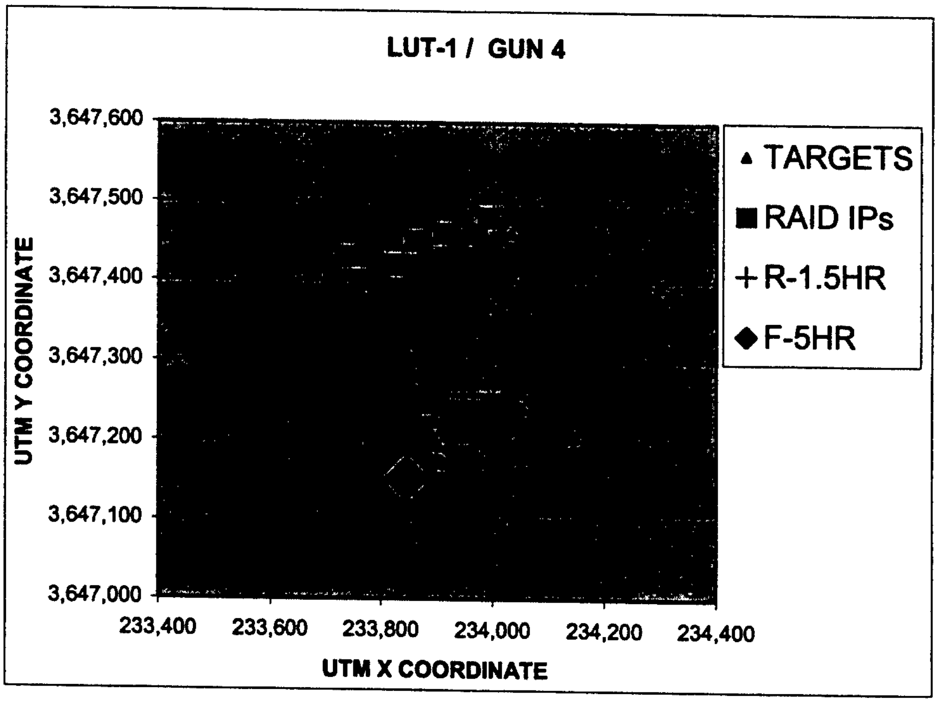


Figure B-3. RAID and simulated impacts for LUT-1/Gun 4.

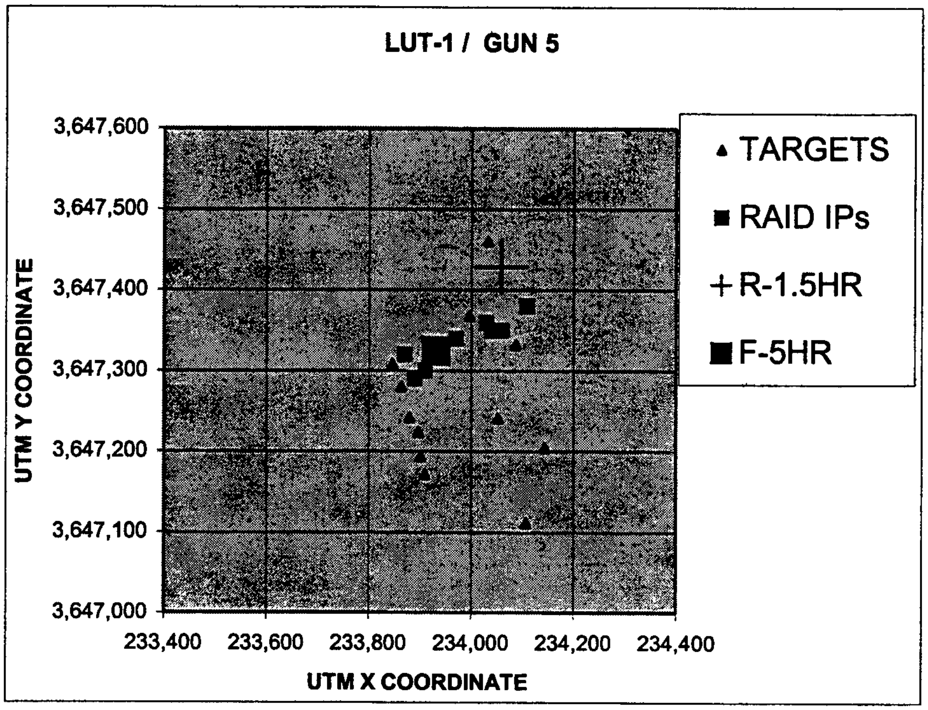


Figure B-4. RAID and simulated impacts for LUT-1/Gun 5.

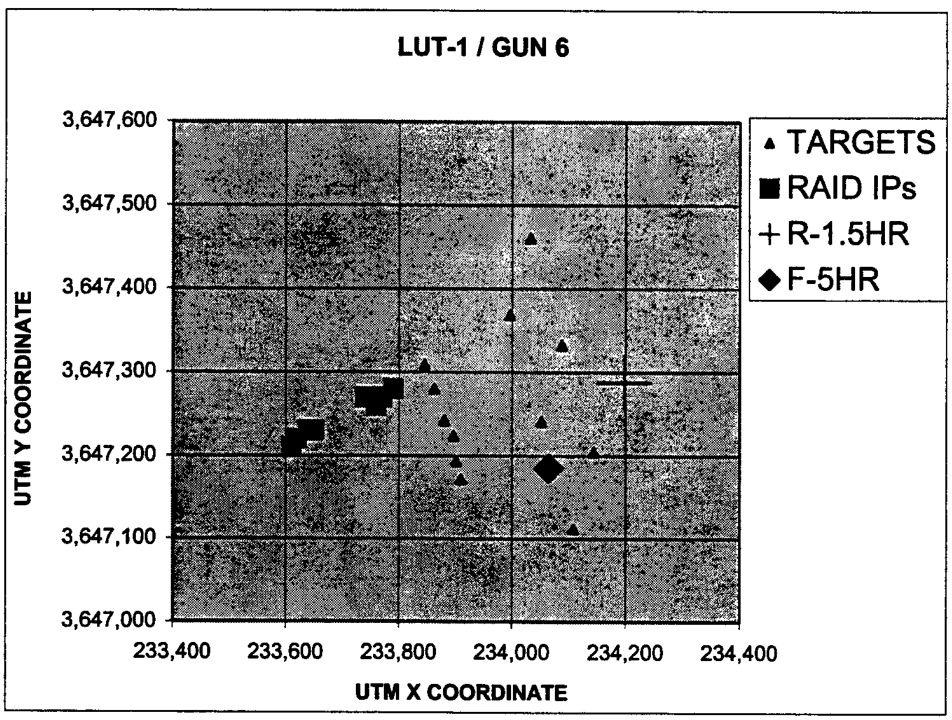


Figure B-5. RAID and simulated impacts for LUT-1/Gun 6.

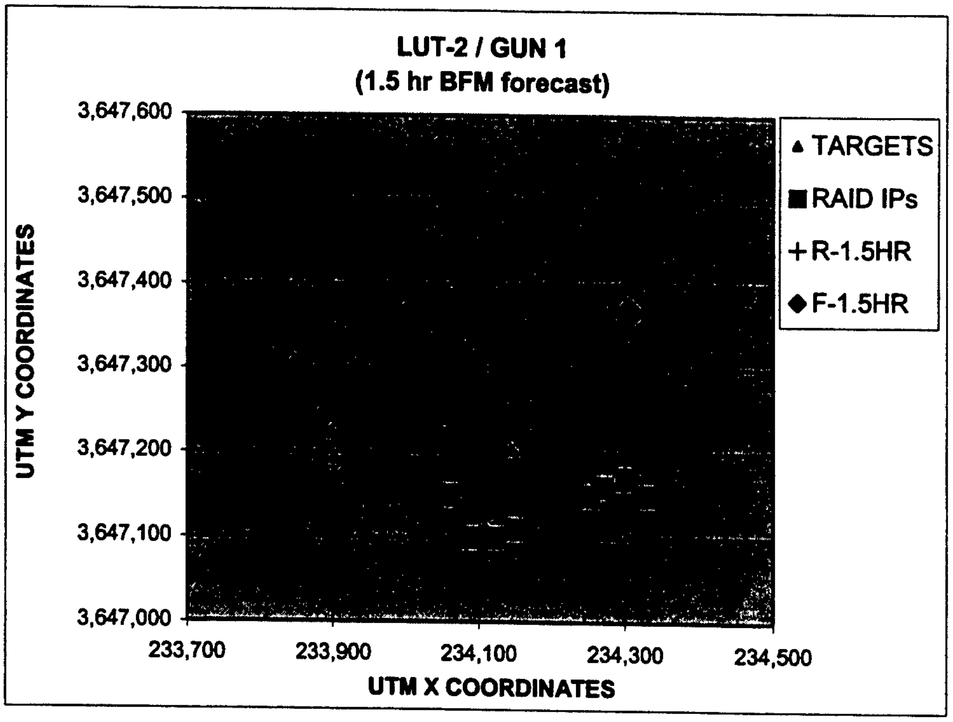


Figure B-6. RAID and simulated impacts for LUT-2/Gun 1.

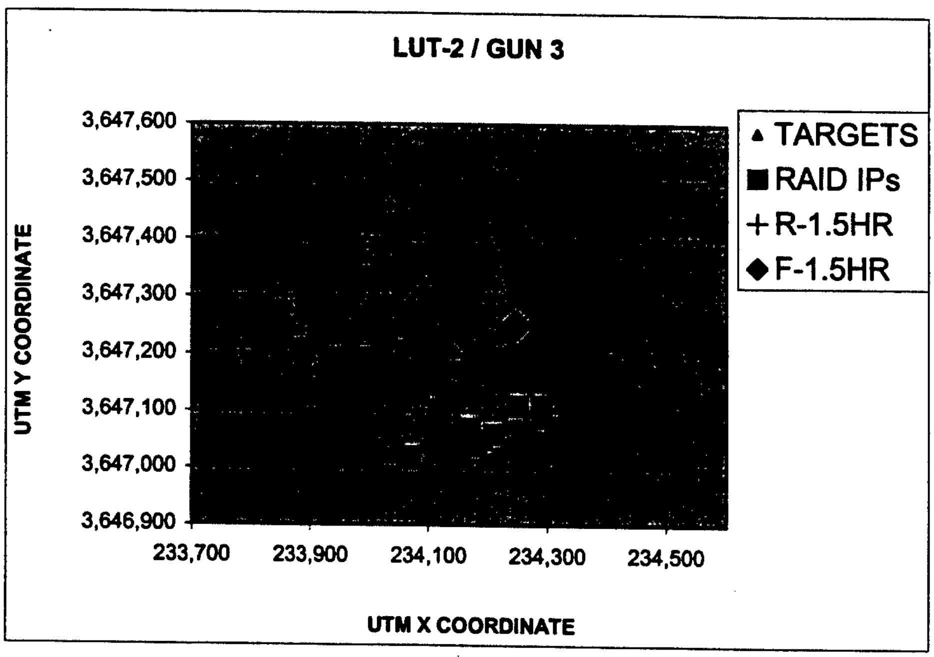


Figure B-7. RAID and simulated impacts for LUT-2/Gun 3.

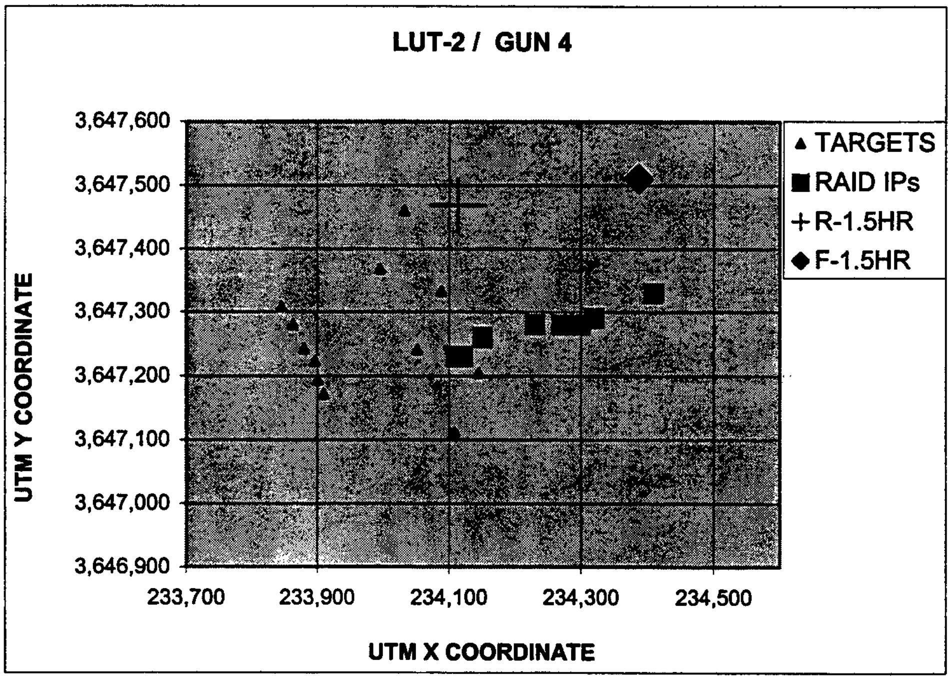


Figure B-8. RAID and simulated impacts for LUT-2/Gun 4.

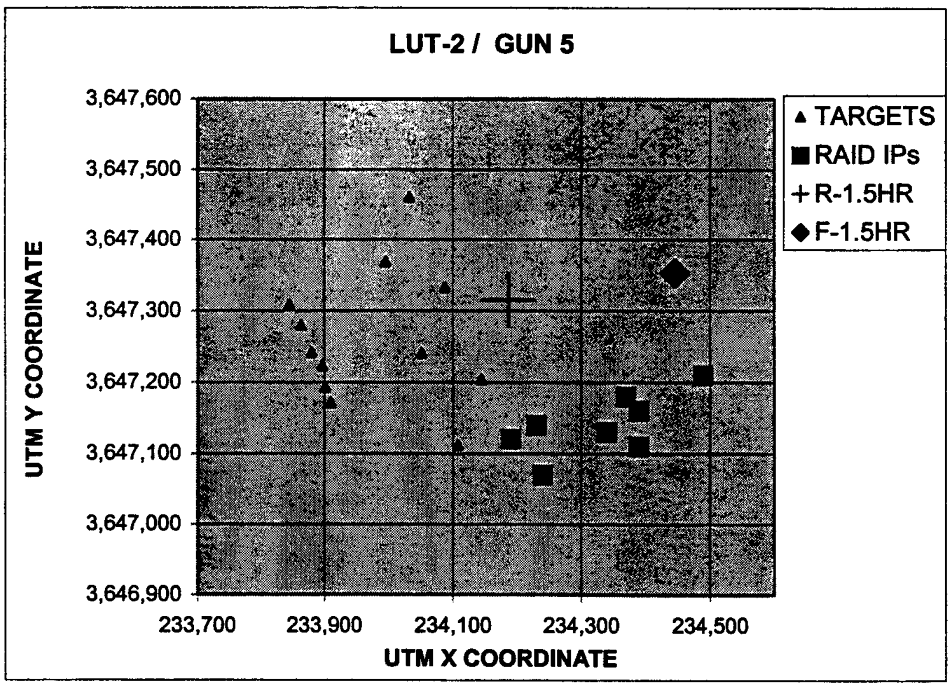


Figure B-9. RAID and simulated impacts for LUT-2/Gun 5.

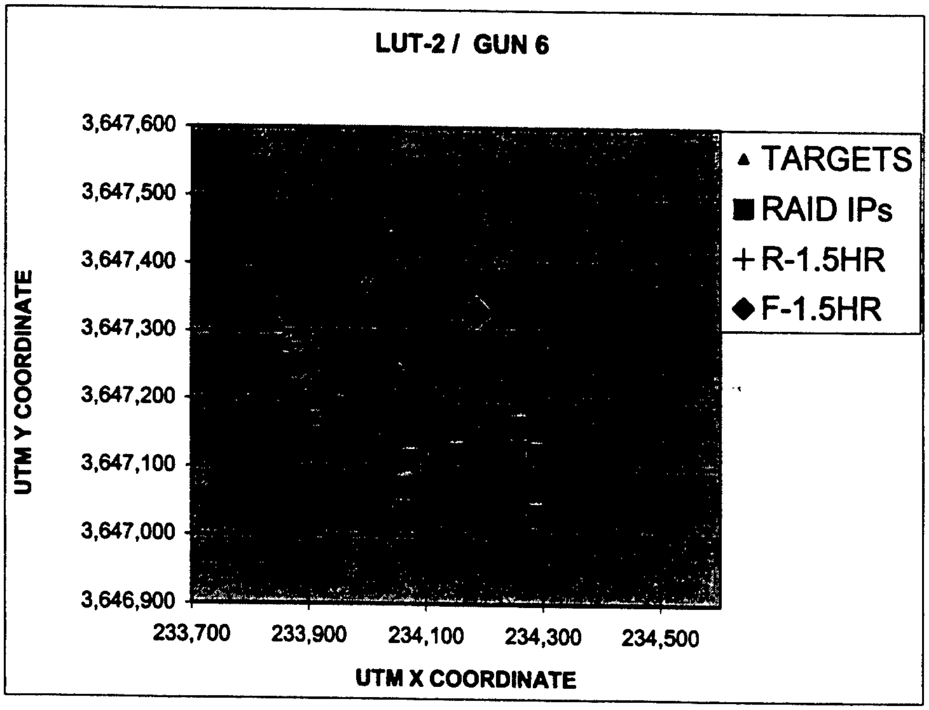


Figure B-10. RAID and simulated impacts for LUT-2/Gun 6.

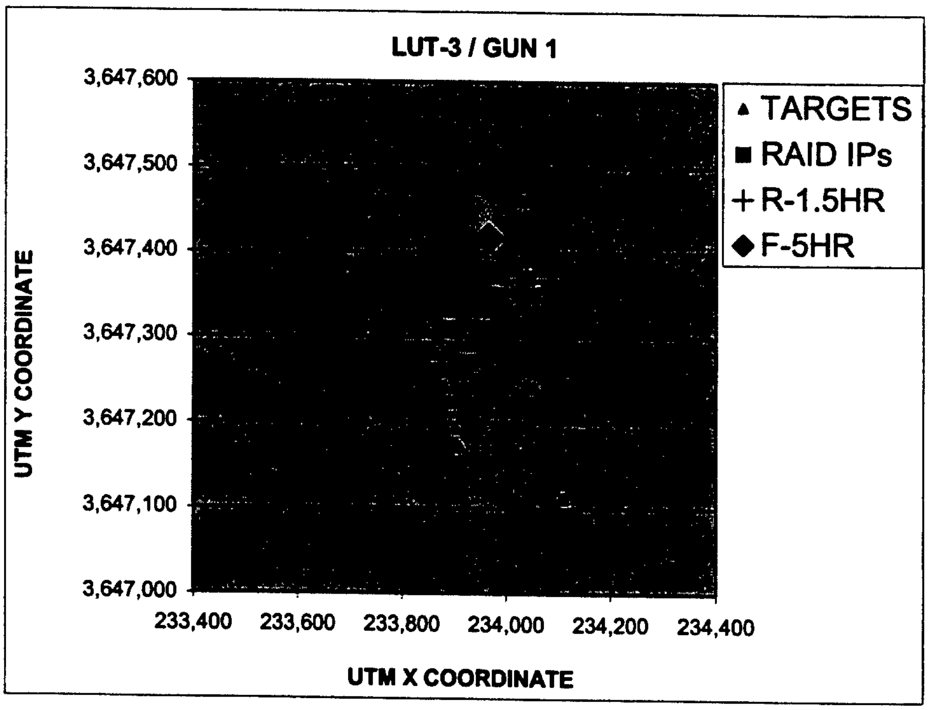


Figure B-11. RAID and simulated impacts for LUT-3/Gun 1.

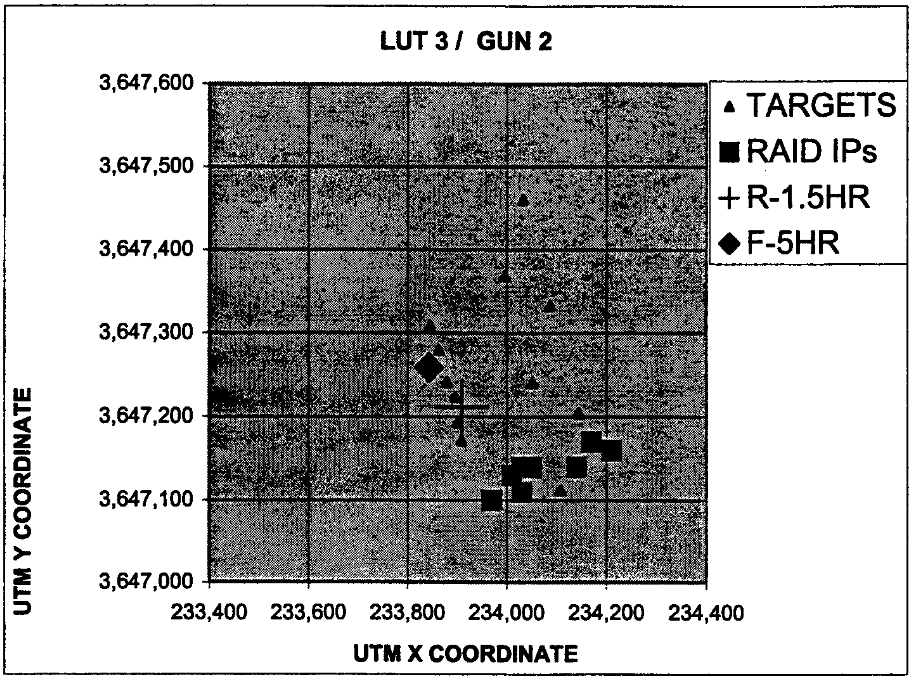


Figure B-12. RAID and simulated impacts for LUT-3/Gun 2.

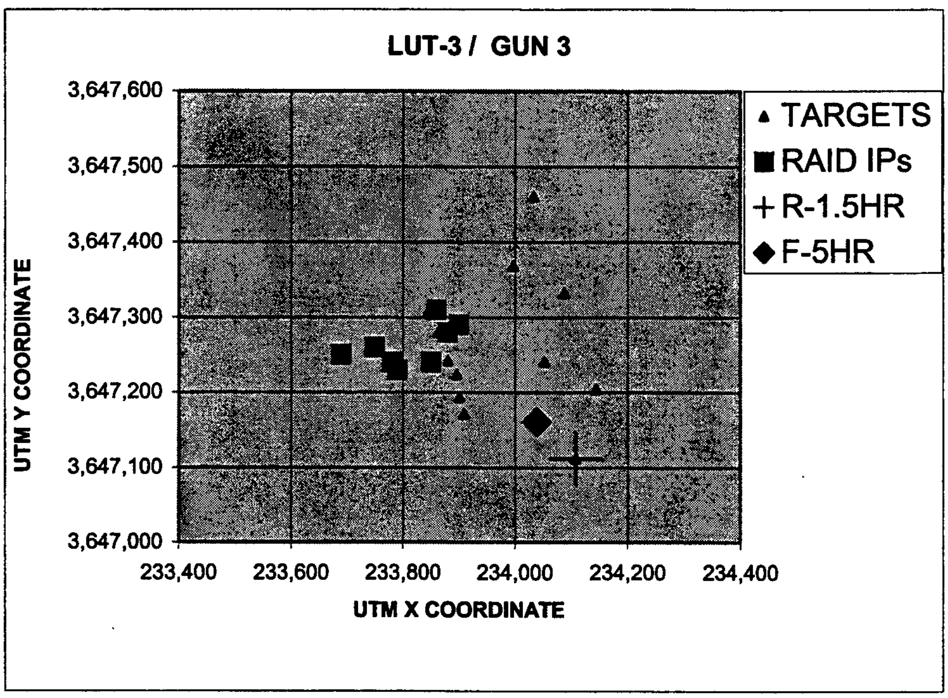


Figure B-13. RAID and simulated impacts for LUT-3/Gun 3.

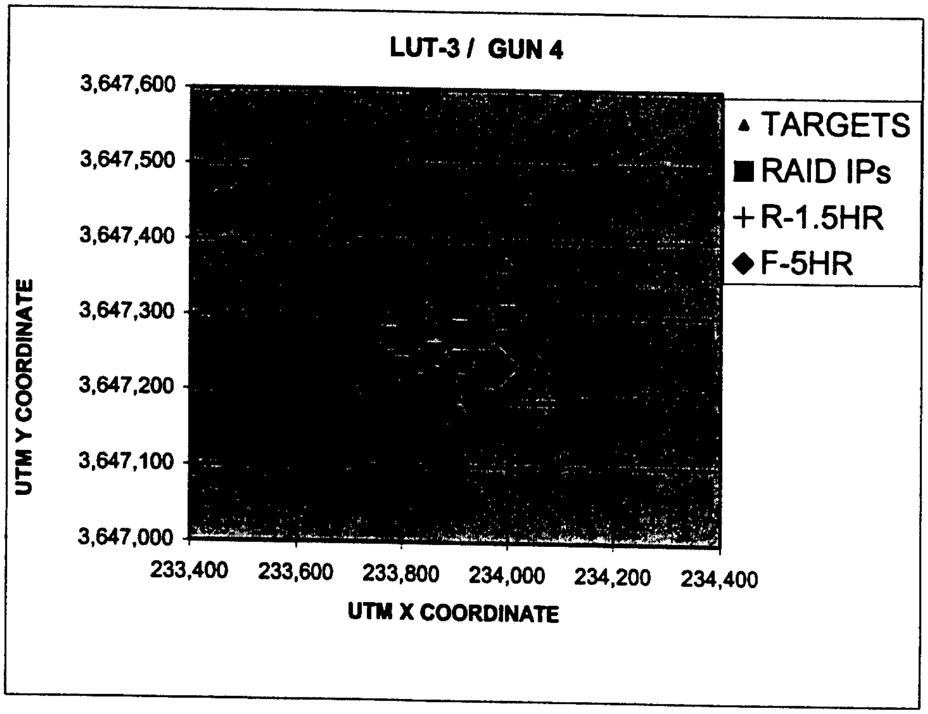


Figure B-14. RAID and simulated impacts for LUT-3/Gun 4.

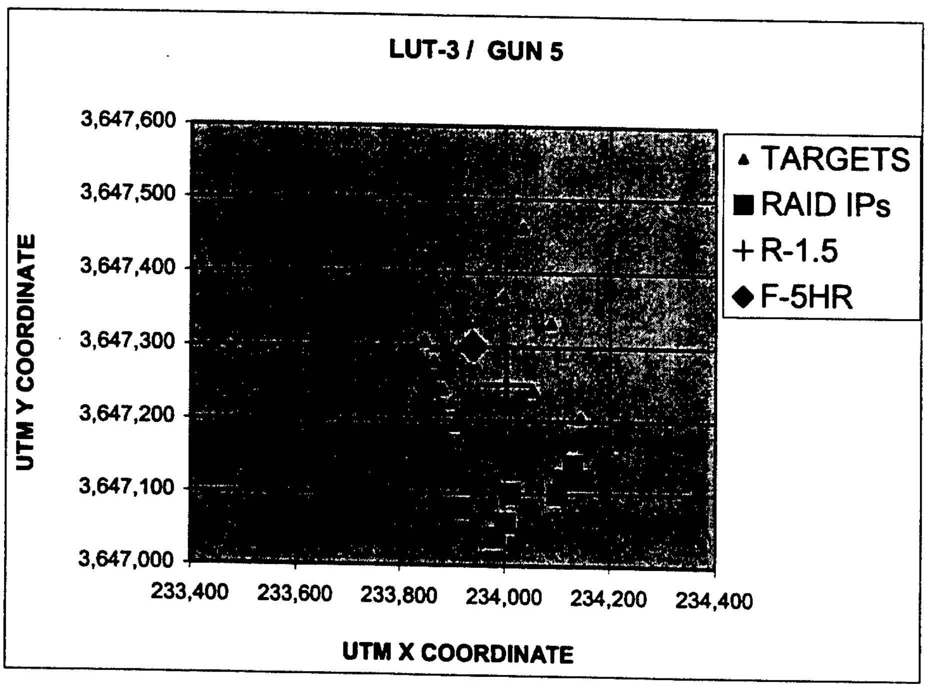


Figure B-15. RAID and simulated impacts for LUT-3/Gun 5.

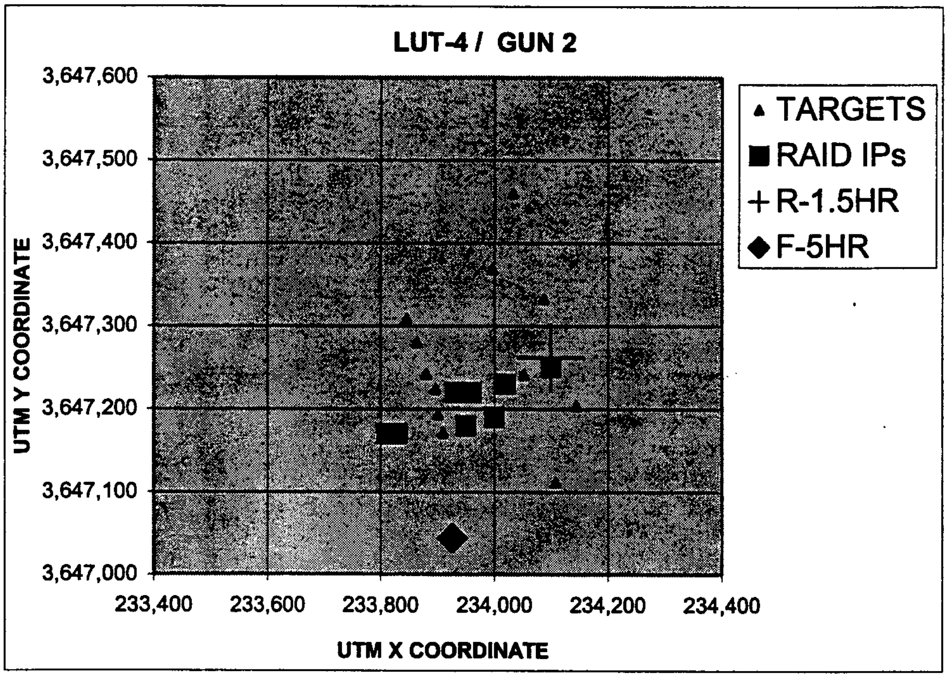


Figure B-16. RAID and simulated impacts for LUT-4/Gun 2.

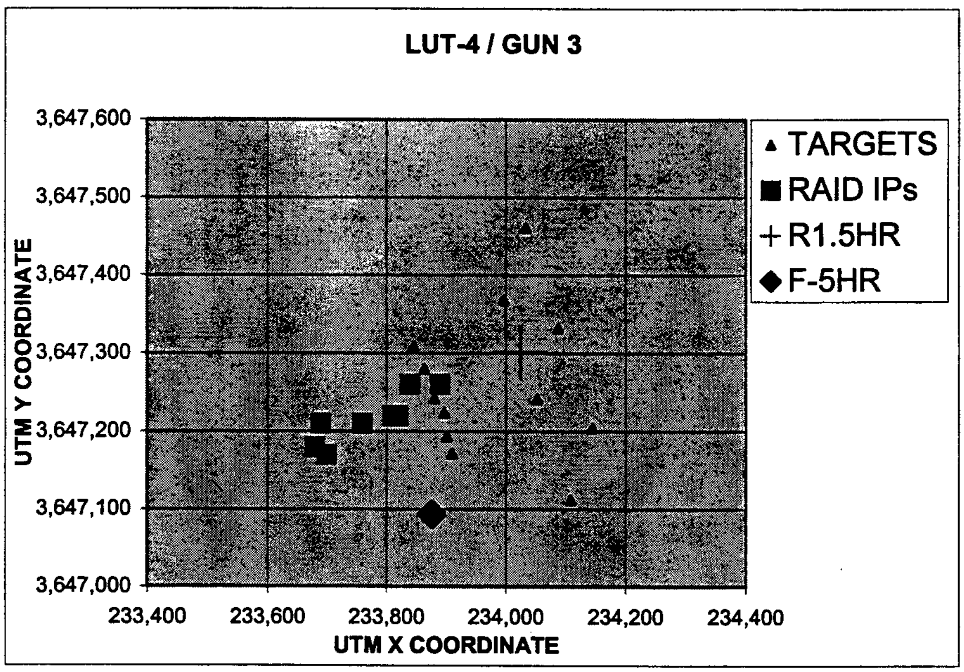


Figure B-17. RAID and simulated impacts for LUT-4/Gun 3.

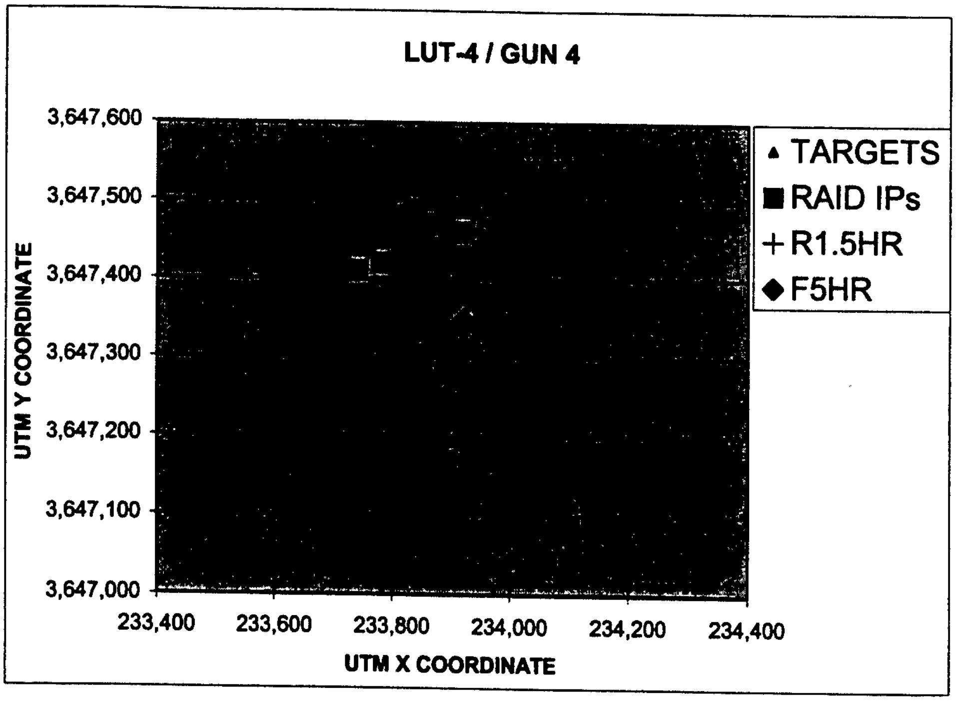


Figure B-18. RAID and simulated impacts for LUT-4/Gun 4.

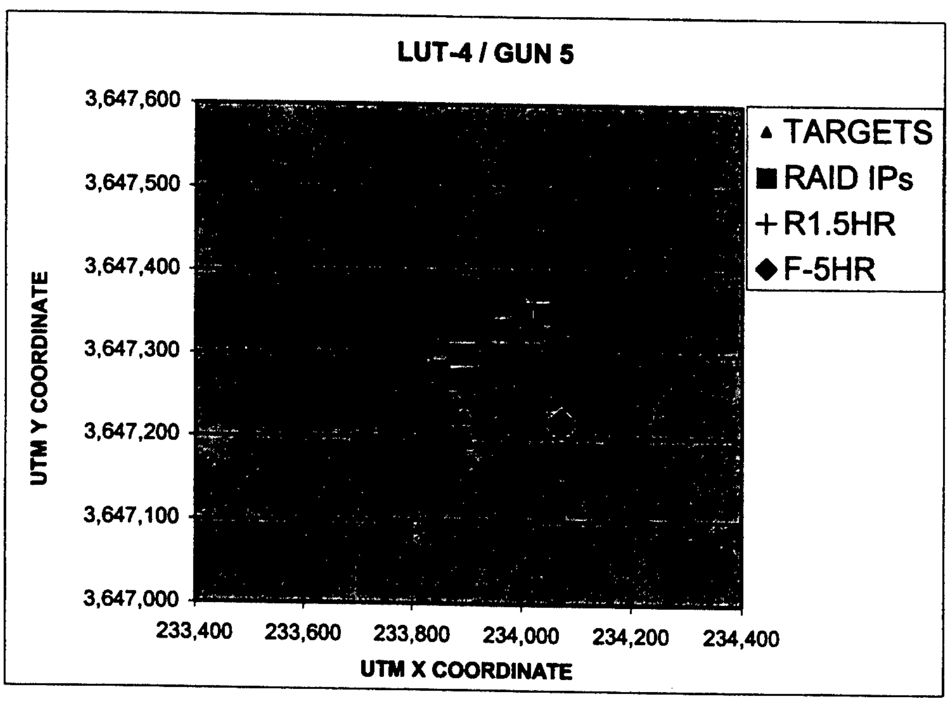


Figure B-19. RAID and simulated impacts for LUT-4/Gun 5.

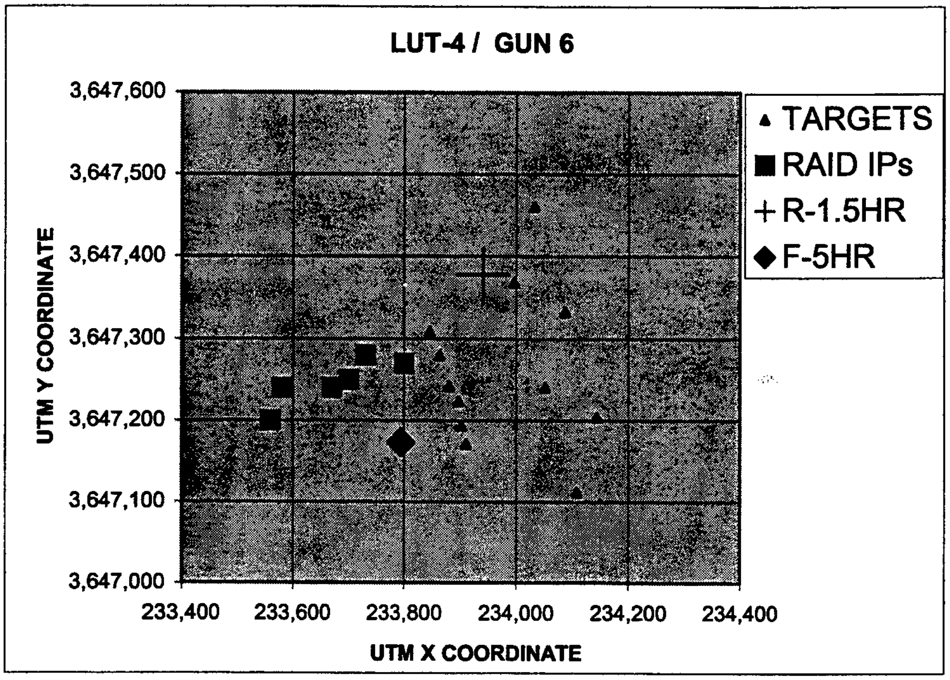


Figure B-20. RAID and simulated impacts for LUT-4/Gun 6.

INTENTIONALLY LEFT BLANK

Appendix C: Acronyms

AGL	above ground level
ARDEC	Armament Research, Development, and Engineering Center
ARL	Army Research Laboratory
BCS	battery computer system
BFM	battlescale forecast model
CMM	computer met message
EFP	explosively formed penetrator
FCMM	forecast computer met message
GTRAJ3	general trajectory model – Version 3
HOTMAC	higher order turbulence model for atmospheric circulations
IOT&E	initial operational test and evaluation
IP	impact point
LUT	limited user test
MET	meteorological
MET-TALL	meteorology – target area low level
MRMD	mean radial miss distance
NOGAPS	Navy Operational Global Atmospheric Prediction System
OPM-ARMS	Office of the Project Manager – Artillery Munitions Systems
RAID	ram-air inflated decelerator
RAOB	rawinsonde (radio wind sounding) observation
RCMM	RAOB-based CMM
RDAP	reliability determination/assessment program
RMD	radial miss distance
SADARM	sense and destroy armor
TE	true east
TN	true north
TRN	tube round number
UTC	universal time coordinate
UTM	universal transverse mercator
VRP	vortex ring parachute
YPG	Yuma Proving Ground
3DOBJ	3-D objective analysis

INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
December 2002

2. REPORT TYPE
Technical Report/Final

3. DATES COVERED (From - To)

4. TITLE AND SUBTITLE
Effects on SADARM Trajectory Simulations With Local RAOBs and BFM Data for the RDAP/LUT Firings

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Jameson, T. C.; Luces, S. A.; Knapp, D. I. (all of ARL)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
Computational & Information Sciences Directorate
Battlefield Environment Division (ATTN: AMSRL-CI-EB)
White Sands Missile Range, NM 88002-5501

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-2720

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
2800 Powder Mill Road
Adelphi, MD 20783-1145

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
ARL-TR-2720

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This report describes meteorological analyses of data collected during the sense and destroy armor (SADARM) reliability determination/assurance program (RDAP) and limited user test (LUT) firings that occurred during the winter and spring of 2000 at Yuma Proving Ground, Arizona. The study was proposed as a way to further evaluate current and future artillery meteorological forecasting capabilities to improve SADARM targeting accuracy. Ballistic trajectory simulation analyses using raw and forecast meteorological values and corresponding actual impact data from the RDAP and LUT firings are presented.

15. SUBJECT TERMS
battle scale forecast model, mean radial miss distance, rawinsonde observation, submunition, general trajectory model, ram-air inflated decelerator, SADARM, trajectory simulator

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U		54	Terry Jameson
					19b. TELEPHONE NUMBER *(Include area code)* 505-678-3924

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18